PB-239 926

ASSESSMENT OF PARTICLE CONTROL TECHNOLOGY FOR ENCLOSED ASBESTOS SOURCES

IIT Research Institute

PREPARED FOR
National Environmental Research Center

October 1974

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-650/2-74-088	2.	3. PB 239 926

4. TITLE AND SUBTITLE Assessment of Particle Control Technology for Enclosed Asbestos Sources	5. REPORT DATE October 1974 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Colin F. Harwood, Paul Siebert, and Thomas P. Blaszak	8. PERFORMING ORGANIZATION REPORT NO. C6291-11
9. PERFORMING ORGANIZATION NAME AND ADDRESS II T Research Institute 10 West 35th Street Chicago, Illinois 60616	10. PROGRAM ELEMENT NO. 1AB015; ROAP 21AFA-006 11. CONTRACT/GRANT NO. 68-02-1353
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final; 6/73-5/74 14. SPONSORING AGENCY CODE

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

15. SUPPLEMENTARY NOTES

16. ABSTRACT The report gives results of a study to provide information, from both the literature and user contact, on the control of asbestos emissions from enclosed sources. It assesses the state-of-the-art in asbestos emission control in terms of the devices or methods used and their efficiency. In addition, it gives results of a preliminary study to actually measure the effectiveness of baghouse control devices in controlling emissions from five asbestos plants. Baghouses are the predominant control device used in the asbestos industry. Cotton bags are used most frequently. Automatic shaking is used in most baghouses, with shake cycles of 1-1/2 to 4 hours most common. Most baghouses operate at two pressure drop ranges, 2.5-5 and 7.5-10 cm H2O. Air-to-cloth ratios range from 2 to 10:1. Published data on the removal efficiencies of the control devices was either non-existent, or quoted in general terms. Five baghouses were tested for removal efficiency in terms of mass and fiber number: although mass efficiency was very high, fiber concentrations exceeding 100 million fibers/cu meter, greater than about 0.05 μm long, are emitted. Using computer modeling, it was found that, even considering one source, asbestos concentrations of 500 f/cu meter can be anticipated 5 km from the source. The exposure level at which asbestos in ambient air becomes a health hazard is not known.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Cyclone Separators	Air Pollution Control	13B , 07A
Asbestos	Scrubbers	Stationary Sources	08G
Fibers	Efficiency	Enclosed Sources	11E
Dust		Particulate	11G
Dust Collectors		Baghouses	13A
Measurement		Fabric Filters	14B

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 136
	20. SECURITY CLASS (This page) Unclassified	22. PRICE 5.75

PRICES SUBJECT TO CHANGE

EPA-650/2-74-088

ASSESSMENT OF PARTICLE CONTROL TECHNOLOGY FOR ENCLOSED ASBESTOS SOURCES

by

C. F. Harwood, P. Siebert, and T. P. Blaszak

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

Contract No. 68-02-1353
ROAP No. 21AFA-006
Program Element No. 1AB015

EPA Project Officer: D. K. Oestreich

Control Systems Laboratory
National Environmental Research Center
Research Triangle Park, North Carolina 27711

Prepared for

OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

October 1974

ia

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

The report gives results of a study to provide information, from both the literature and user contact, on the control of asbestos emissions from enclosed sources. It assesses the state-of-the-art in asbestos emission control in terms of the devices or methods used and their efficiency. In addition, it gives results of a preliminary study to actually measure the effectiveness of baghouse control devices in controlling emissions from five asbestos plants. Baghouses are the predominant control device used in the asbestos industry. Cotton bags are used most frequently. Automatic shaking is used in most baghouses, with shake cycles of 1½ to 4 hours most common. Most baghouses operate at two pressure drop ranges, 2.5-5 and 7.5-10 cm H_2O. Air-to-cloth ratios range from 2 to 10:1. Published data on the removal efficiencies of the control devices was either non-existent, or quoted in general terms. Five baghouses were tested for removal efficiency in terms of mass and fiber number: although mass efficiency was very high, fiber concentrations exceeding 100 million fibers/cu meter, greater than about 0.05 μm long, are emitted. Using computer modeling, it was found that, even considering one source, asbestos concentrations of over 500 fibers/cu meter can be anticipated 5 km from the source. The exposure level at which asbestos in ambient air becomes a health hazard is not known.

This report was submitted in fulfillment of IITRI Project Number C6291, Contract Number 68-02-1353, by the IIT Research Institute, under the sponsorship of the Environmental Protection Agency. Work was completed as of May 1974.

CONTENTS

Page

Abstract iii

List of Figures v

List of Tables vi

Acknowledgements viii

Sections

1 Conclusions 1

2 Recommendations 3

3 Introduction 5

4 Literature Survey 6

5 Compilation of Control Equipment User's Data 26

6 Emission Data Collection and Analysis 43

7 Estimate of Asbestos Dispersion 67

8 References 79

9 Appendices 82

FIGURES

No.		Page
1	Sampling Arrangement	45
2	Coordinate System Showing Gaussian Distributions in the Horizontal and Vertical	68
3	The Concentration of Asbestos Fibers with Distance from Source at Four Stability Conditions for Johns-Manville, Waukegan, Illinois	74
4	The Concentration of Asbestos Fibers with Distance from Source at Four Stability Conditions for Johns-Manville, Denison, Texas	75
5	The Concentration of Asbestos Fibers with Distance from Source at Four Stability Conditions for Raybestos, Marshville, North Carolina	76
6	The Concentration of Asbestos Fibers with Distance from Source at Four Stability Conditions for Johns-Manville, Asbestos, Canada	77
7	The Concentration of Asbestos Fibers with Distance from Source at Four Stability Conditions for GAF, Eden Mills, Vermont	78

TABLES

No.		Page
1	Filter Fabric Properties	13
2	Fabric Filter Applications -- Asbestos Mining and Manufacturing	19
3	Rule-of-Thumb Costs of Typical Collectors, Standard Mild Steel Construction	22
4	Typical Costs for the Canadian Asbestos Industry	23
5	Product Manufactured	28
6	Size of Asbestos Manufacturing Plants	29
7	Types of Asbestos Processed in Plants	30
8	Dust Control Devices	31
9	Method of Waste Disposal	32
10	Baghouse Manufacturers	35
11	Capacity of Dust Collection System	36
12	Air-to-Cloth Ratio	37
13	Bag Fabric	39
14	Bag Cleaning Mechanism	40
15	Bag Cleaning Cycle	41
16	Pressure Drop Across Bags	42
17	Samples and Sampling Conditions	60
18	Sample Weights and Mass Efficiency Data	61
19	Total Fiber Counts and Fiber Removal Efficiencies	62
20	Optical Microscope (500X) Size Distributions and Fractional Removal Efficiencies	63
21	Electron Microscope (16,364X) Size Distributions and Fractional Removal Efficiencies	64

TABLES (cont.)

No.		Page
22	Key to Stability Categories	71
23	Dispersion Equation Source Terms	73

ACKNOWLEDGEMENTS

The help and cooperation of the asbestos industry is acknowledged. In particular, Johns-Manville, Raybestos, and the GAF Company, who gave the permission for their baghouses to be sampled, and assisted in the setting up of the sampling platforms.

The help and guidance of the original Project Officer, Mr. Dennis Drehmel, and his successor, Mr. David Oestreich, is acknowledged.

IITRI personnel who contributed to this program were David Becker, who produced the bibliography, Scott Preece, who obtained dispersion data through the CDM computer model, Erdmann Luebcke, who undertook field sampling and optical counting, and Anant Samudra, who obtained electron microscope data. The Project Leader was Dr. Colin F. Harwood, assisted by Paul Siebert and Tom Blaszak. John Stockham had fiscal responsibility for the program.

SECTION 1

CONCLUSIONS

A survey of the literature has revealed that there has been little reported on the specific problem of reducing asbestos emissions to the atmosphere. A state-of-the-art review of dust collection has been made, and its application to asbestos has been stressed whenever possible. The literature cites the baghouse as being the prime collector used in the industry.

Information obtained from asbestos product manufacturers confirmed that baghouses are the predominant dust collection device used. Typically, baghouses in the asbestos industry use cotton fabric bags. The cleaning cycle is automated with 1½ to 4 hours separating shake cycles. The usual operating capacity is 140 to 570 cubic meters per minute (5,000 to 20,000 cfm), with an air-to-cloth ratio of just under 3:1. Baghouses are normally free of operating problems. Normal installation costs range from $88.00 to $106.00 per cubic meter per minute ($2.50 to $3.10 per cfm) with operating costs ranging from $1.80 to $35.00 per cubic meter per minute per year ($0.05 to $1.00 per cfm per year).

It is not common practice for the users of the baghouses to measure the efficiencies of their baghouses. No hard data on baghouse efficiency was obtained from users or from the literature. Preliminary field measurements undertaken during this study have confirmed the high efficiency of the baghouse in removing asbestos fiber from the air stream.

Both the mass efficiencies and measured fractional efficiencies are 99+%. However, the dust load is high, resulting in large numbers of fibers being emitted despite high efficiencies. Emissions of about 10^4-10^5 fibers/m^3 of >1.5 µm and 10^7-10^8 fibers/m^3 of <1.5 µm were found to be usual.

The dispersion of asbestos fibers from a source was calculated using the Binomial Continuous Plume Dispersion Model (BCPDM) and the Climatological Dispersion Model (CDM). The CDM model is designed to develop a long-term, quasi-stable pollutant concentration profile for a given area. Unreliable results were obtained using this model, which showed that it was not suited for the particular conditions of this study. The exact cause of the failure was not established.

Results obtained with the BCPDM model were consistent. As expected, the estimated concentration values varied with the size of the emission source, the time of day, and the distance from the plant. At a distance of 1 kilometer from the plant, peak values of about 10^3 to 10^7 fibers per cubic meter were calculated. A sharp decline was observed to about 10 kilometers distance, where the concentrations of about 2.5×10^1 to 5×10^6 fibers per cubic meter were calculated. Beyond 10 kilometers, the rate of decline of the fiber concentration was slow, at a distance of 30 kilometers, the values were calculated to be about 10^1 to 10^6 fibers per cubic meter.

It is stressed that these values extend from a single source. Fiber emissions from other baghouses within the same plant and from adjacent plants would lead to increased ambient concnetrations.

SECTION 2

RECOMMENDATIONS

This study has shown that current control devices emit very large numbers of small fibers. It is estimated that these fibers remain suspended and travel large distances from the source. It is recommended that methods to reduce these emissions should be investigated.

Since baghouses are the accepted best method of reducing asbestos emissions, the most logical study would be to optimize the baghouse performance. A statistically designed experimental study would establish the efficiency controlling parameters. Baghouses could then be optimized to control emissions from specific asbestos waste types.

While initial consideration should be given to optimizing baghouses, other types of devices should not be overlooked. It is recommended that both established and novel control devices be considered and tested either singly or in combination with baghouses. For example, novel systems, such as foam injected cyclones, and established devices, such as electrostatic precipitators, have not been evaluated for asbestos emission control.

It is also recommended that studies should be conducted to establish the fate of emitted asbestos fibers. The small size of the fibers, and their indestructable nature, implies that they may remain suspended indefinitely. The limited particle scavenging studies that have been conducted do not include fibrous particles. Studies on approximately spherical, sub-micron particles indicate that scavenging by snow and rain is of ultra low efficiency. Implicit in the long-term suspension of these fine fibers, their chemical inertness, and the lack of an effective scavenging mechanism, is the possibility that the number of asbestos particles in the atmosphere is increasing. A test program is recommended to determine if this is true and, if so, its health significance.

SECTION 3

INTRODUCTION

The control of hazardous emissions from operations involving asbestos products is mandatory under the application of the Clean Air Act. It is, therefore, necessary for the Environmental Protection Agency to evaluate the control technology applicable to enclosed sources of these hazardous emissions. In this way, it is possible to introduce legislation which will require the application of operating practices capable of protecting the public health. The applicability and effectiveness of these practices will be supported by sound scientific procedures and experimental evidence.

To develop the information required for this report, three methods were used:

1. The scientific literature was surveyed and a bibliography produced. Published literature pertinent to the control of asbestos emissions from enclosed sources was reviewed.
2. Users and manufacturers of emission control equipment were contacted. Information on equipment applicabilities and the attainable degree of control with various control approaches was solicited.
3. Sampling and analysis were conducted to obtain data on the emissions from five different enclosed sources. These manufacturing sources were selected because the control technology employed was typical of the industry.

SECTION 4

LITERATURE SURVEY

INTRODUCTION

Literature Search

The literature on emission control of asbestos has been surveyed by computer search. Very few references specific to asbestos have been found; for this reason, the search was broadened to include industries with related particulate emission problems.

A bibliography has been produced; because of its large size, it has been bound under separate cover from the main report. It is some 231 pages in length and contains over 3,000 citations. References have been arranged by KWIC (key word in context), by author, and by citation.

Abstracts of pertinent references are included in Appendix A.

Types of Control Devices

The major types of collection devices available are cyclones, wet scrubbers, electrostatic precipitators, and baghouses. Each of these devices has some applicability in the asbestos industry, although in the United States, baghouses are generally used as the final control device. Cyclones are inertial collectors, which collect particles by imparting a tangential velocity to the gas stream, so that the particles are moved by centrifugal forces to the cyclone wall, where they are collected.

Wet spray collectors, which are designed in a wide variety, operate by atomizing or breaking down liquid droplets to an extremely fine spray. The increased water surface area allows better contact with the particles and improves the chances that the contaminants will be captured. The waste, a wet slurry, is then removed from the gas stream by either centrifugal or mechanical means.

Electrostatic precipitators are essentially a chamber with a series of high voltage electrodes between grounded plates. The corona around the discharge electrodes ionizes the gas, and, therefore, the dust which then migrates to the plates. The particles then fall, or are rapped loose or washed into hoppers. Micron and sub-micron material can only be collected by high efficiency bag filters, high efficiency scrubbers, or ESP's.

Baghouses utilize fabric filters in a bag or tubular shape, which are mounted either in the plant itself or in separate modules. As particles are collected, they build up a filter cake which increases collection efficiency and the pressure drop across the filter. Occasionally, this filter cake must be removed, as the power required to overcome the pressure drop becomes too high.

Use in the Asbestos Industry

In asbestos mining, small fabric filters are used for control during drilling. Cyclones, bag collectors, and properly designed ducts are then used for dust control in the crushing operation. Cyclones, sometimes followed by baghouses, are used as control devices on the dryers.

Asbestos milling involves crushing and separation from the dust by air aspiration, grading of the fibers by cyclones connected to the baghouse. Also connected to the baghouse are the screens, separators, recirculating systems, regrading areas, pressure packers, and other dust control systems, i.e., vacuum systems. Generally, all conveyors are covered, and low velocity hoods are used for control of dust in other areas. (In many asbestos processing operations in which dust occurs, i.e., textiles and friction materials, cyclones and baghouses are also used.) Mill ventilation systems generally receive 50% of their load from the screens, 25% from dust control systems, and the remainder from various machines which open the fiber, separate dust from fibers, or segregate fiber lengths[1]. The milling process generally requires 9-10 tons air/ton ore processed, and approximately 10 ton air/ton finished product[2,3,4].

The properties of asbestos which complicate its cleaning from ventilation air are[5]: 1) its fibrous nature, i.e., it tends to interlace and mat, thus creating pneumatic handling difficulties; 2) its friability, or ability to break down to smaller and smaller fibers so that a high efficiency is needed for sizes less than 10 μm; 3) as the size of the fibers decreases, they become increasingly affected by moisture so that an impenetrable cake is formed; 4) its low apparent specific gravity, which is one-fourth to one-fifth of its real specific gravity of 2.54-2.59, so that it is less easily collected by gravitational or inertial techniques.

CYCLONES

Cyclones are generally efficient collectors for particles which have diameters greater than 10-20 μm. Low efficiency cyclones can be used for 10-20 years in a high temperature, non-corrosive environment; however, their efficiencies are only 80% for particles greater than 44 μm[6]. High efficiency cyclones utilize a much smaller diameter and various other design refinements to achieve much higher efficiencies at the cost of a greater pressure drop. Due to their small diameters and correspondingly small flow capacities, high efficiency cyclones are usually used in multiple units. These multiple cyclones are capable of collection efficiencies of 100% for particles larger than 10 µm, and greater than 90% for particles larger than 2 µm[6]. Cyclones have the advantages of[7]: 1) simple design; 2) easy protection against wear; 3) high efficiency if scientifically designed; and 4) automatic locks to prevent leakage. Its major disadvantage is that for high efficiencies for micron-sized particles, very small diameters susceptible to clogging and wear are needed. For the large capacities needed for asbestos applications, small diameter, high efficiency cyclones are generally not practicable. In one asbestos mill in Quebec, twin cyclones of 2 m diameter were used from 1960-67 as the primary control device. The collection efficiency achieved was only 70%, so that they had to be replaced when stricter emission regulations were effected[8].

Generally, low efficiency cyclones are used in asbestos milling to collect most of the fiber and a minimum of rock dust in the separation process[1,4]. Cyclones are also used for the grading of asbestos into specific size ranges[9]. Also, they are frequently used as pre-cleaners before the final control device, which is usually a baghouse[2].

WET SPRAY COLLECTORS

Wet spray collectors are available in a variety of designs, including the following[6,7].

1. Water injection into fans modified with special fittings for ultrafine atomization of water. A single fan can clean up to 100,000 m^3/hr (59,000 cfm) with a water flow of 0.1-0.3 lpm (0.026-0.079 gpm).

2. Water sprayed filter beds containing several layers of specially shaped elements. The gas velocity is less than 2 m/sec previous to the injection of droplets from the spray wash at a flow of approximately 0.14 m^3, depending on the type and size of the dust.

3. Wet centrifugal scrubbers are more efficient than dry centrifugal devices such as cyclones; however, they have a greater corrosive action, tend to plug, and are more expensive to operate.

4. Water sprays scrubbers are designed so that the air stream decelerates when the spray contacts it.

5. Baffle box scrubbers pull the dirty gas through several inches of turbulent water, sometimes using centrifugal action.

6. Venturi scrubbers atomize the water droplets by injection at high pressure into the high air velocity at the throat of the venturi section. As the venturi area increases, the larger droplets are still accelerating, while the gas and particles are decelerating, thus creating a second area of collection of particles on drops. Venturis operate at a liquid-to-gas ratio of approximately 0.2-0.9 ℓ/m^3 and are capable of achieving efficiencies of 90-99% for particles less than 1 μm.

All wet collectors have the disadvantages of requiring some water treatment for the wet slurry produced, and often for its removal from the gas stream. They can also require large amounts of water if the water in the slurry is not easily recycleable.

The experience with wet collectors as the primary control device in two mills showed the following difficulties: 1) blocking of the device; 2) corrosion; 3) difficulties in disposing of slurry products; and 4) overall efficiencies of 85-95%[8]. In wet processes used in some asbestos operations, wet collectors are required, due to the nature of the operation. Wet processes are not generally used; they generate production difficulties because of the time required to dry the product. They also require additional handling after drying[5].

ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators are capable of cleaning a large volume of gas at high flow rates, temperatures, and humidities. A dry process gas requires either a very large precipitator, or a large humidity tower before cleaning[10]. The advantages of electrostatic precipitators are[7,5,8]: 1) no limits on theoretical efficiency achievable by design; 2) low pressure drop across the collector and, therefore, low fan power required; 3) exceptional reliability; 4) low operating cost for total power required of approximately 0.23 kW/100 m^3/hr; and 5) simple construction. Their disadvantages are[5]: 1) a high installation cost, which increases exponentially with efficiency; 2) the design must be for a specific dust concentration; and 3) small particles may create a visible effluent, even though they are 98-99% efficient on a mass basis.

Electrostatic precipitators are very rarely used for asbestos processes in the United States; however, they are more widely used in the United Kingdom. They have very high theoretical efficiencies, but for these efficiencies to be achieved, the process must be rigidly controlled with respect to particle velocity, moisture content, temperature, and dust concentration[8]. As asbestos milling produces a highly variable load, the design must be for a median operation, so that it will not achieve maximum design efficiency during normal operation[5].

BAGHOUSES

Fabric Selection

Baghouses (or fabric filters) are very efficient (95-99.9%) for smaller gas flows, if the temperature and humidity are not excessive. The choice of fabric used depends on: 1) temperatures of gas stream; 2) physical and chemical characteristics of the particles collected; 3) the chemical composition of the gas; and 4) the moisture content of the gas[11]. A wide range of fabrics are available with varying characteristics and prices as shown in Table 1. In many applications, the temperature of the gas stream is the limiting factor; however, this is not a major problem in the case of asbestos. The determining fabric characteristics are[12] the fiber used, whether it is woven or felted, its weight, permeability, tensile strength, abrasion resistance, collection efficiency, dimensional stability, whether or not it is napped, and its static charge. A woven fabric is suitable for lower air-to-cloth ratios of 0.46 to 1.24:1 m/min (m^3/min of air/m^2 of cloth, 1.5-4.0:1 cfm/ft^2). With napping and blending, this can be increased to 3.1:1 m/min (10:1 ft/min). Felted cloths are usable at much higher air-to-cloth ratios of 1.24-3.72 m/min (4-12:1 ft/min); however, they are more expensive. Not all fabrics can be felted, and extremely fine particles can become embedded, making cleaning difficult. The weight of the fabric generally ranges from 14-56 g/m^2 (4-16 oz/yd^2). The heavier fabrics have lower thread count of heavy, bulky yarns, include felted fabrics, and are less flexible. The weaves used for dust control range from one over one to four over one, and two or three over two. The higher the sum of the over and under threads, the higher the weight of the fabric, the collection efficiency, and the permeability. The permeability is measured as cfm of air/ft^2 of fabric at a pressure drop of 12.7 mm H_2O (0.5 in). The general practice is to use the most open fabric for the required collection efficiency. The tensile strength (or fiber tenacity in g/denier (fiber)) is recommended to be a minimum of 3.52-7.04 kg/cm^2 (50-100 lb/in.^{2}), while some fabrics, i.e., nylon, have tensile strengths greater than 28.1 kg/cm^2 (400 lb/in.^{2}). If all other factors are constant, increased

Table 1. FILTER FABRIC PROPERTIES

Fabric	Max. Temp. (°F)	Max. Temp. (°C)	Abrasion Resistance	Acid Resistance	Alkali Resistance	Tensile Strength	Moist Heat	Oxidizing Agents	Cost
Cotton	180	82.2	G	P	E	G	P	P	Most Economical
Wool	190	87.8	G	C	P	F	P	P	Economical
Nylon	225	107.2	E	F	E	E	G	F	Low-Moderate
Polypropylene	225	107.2	E	E	E	E	G	G	Moderate
Orlon	260	126.7	G	G	F	G	G	G	Moderate
Acrylic	260	126.7	G	P	F	F	G	G	Moderate
Polyester	275	135.0	E	G	F	G	G	G	Moderate
Nomex	450	232.2	E	G	VG	E	E	G	Expensive
Teflon	475	246.1	F	E	E	G	G	E	Very Expensive
Fiberglass	500	260	P	F	G	E	E	G	Expensive

E - Excellent
VG - Very Good
G - Good
F - Fair
P - Poor

(Table abstracted from Reference 12)

tensile strength implies increased bag life. The abrasion resistance of filament fibers is usually greater than the staple form. The abrasion resistance is one of the critical factors in determining bag life, as it is decreased by either yarn failure by surface abrasion or intrayarn abrasion. The collection efficiency is determined along with the pressure drop by the filter cake, which builds up on a particular fabric. Therefore, the fabric must be strong enough to support the increasing cake, and tight enough to "heal" quickly after cleaning. Dimensional stability is a problem, especially with synthetics, which have a tendency to stretch under high loads, or shrink at high temperature. Either type of change can change the porosity and permeability, i.e., make the fabric too loose or too tight The most dimensionally stable fabrics are glass fibers and dacron. Napping of a fabric exposes more surface area for collection, and thus increases efficiency; however, it makes the fabric more difficult to clean. Napping is useful in light dust loads, low pressure drop, and high air-to-cloth ratio. Static electricity can be a factor in that particles can charge the fabric under certain conditions. This can improve efficiency and/or interfere with cleaning; however, it is generally considered that the detriments outweigh the advantage[12] .

The bag can be arranged in several ways[12,13]. Flat bags have the advantage of a high surface area-to-volume ratio, made possible by bag spacing. Collection is on the outside of the bag, so that if they are too close, the dust will bridge between two bags. Cleaning is usually by mechanical shaking or reverse air. Multiple pocket tube type bags collect dust on the inside, with the disadvantages that there are limitations on the average gas velocity at the seam, and dimensional instability. Single tubular bags are used for either top or bottom entry for inside collection.

Supported tube type bags are needed for collection on the outside of the bag. The bags are usually felt, capable of handling a high air-to-cloth ratio, and are cleaned by some sort of air pulse.

Cleaning Mechanisms

There are several major types of cleaning mechanisms: 1) mechanical shaking, 2) reverse air, 3) pulse air cleaning, or 4) sonic cleaning[12,13]. Mechanical shaking can either be by hand, which requires that section of the unit to be off-stream, or continuous or automatic shaking. This method uses a mechanical device and several preset, usually adjustable, timers to shut down one section of the baghouse at a time for cleaning. Reverse air methods are either of the atmospheric pressure, off-stream variety, which can be combined with mechanical shaking, or the high pressure type, which need not be off-stream. Pulse air cleaning uses a 4.22-7.04 kg/cm^2 (60-100 psig) pulse in supported tubular bags to create a shock wave, which moves the cloth off the supports and dislodges the filter cake. Its major advantage is that, like high pressure reverse cleaning, it can be done while the system is on-line. Sonic cleaning uses a low frequency air power horn or sonic generator operating at 250 cps. This creates a sympathetic vibration in the bags, which shakes loose the cake for cleaning by reverse air flow. Sonic cleaning and other methods, such as bubble cleaning, are very rarely used in practice.

Design Characteristics

The design of a baghouse[5,12,13,14] is decided by the following characteristics of the dust to be collected and the gas stream. The type, size, acidity or alkalinity, and abrasiveness of the dust, along with the moisture and temperature of the air determine the filter fabric to be used. The size of the baghouse is determined by: 1) the dust loading, 2) the estimated air flow, 3) the pressure drop across the fabric, and 4) the gas velocity needed for the filtering characteristics for the particular dust. Bag sizing is determined by the type of cleaning method used with the limitation of a maximum length-to-diameter ratio of 30:1 for a uniform filtration profile from the botton to the top of the tube, and an acceptable entrance velocity at the inlet. Maintenance and inspection considerations require compartment walkways at cell plate and bag suspension level, and that bag grouping and suspension is suitable for effective accessibility.

The critical characteristics[4,12,13] of a baghouse are air-to-cloth ratio (theoretically the same as the linear velocity through the cloth, which actually varies with location), capacity, and pressure drop. The air-to-cloth ratio is generally expressed as the total gas flow in cfm (0.028 m^3/min) divided by the square feet (0.9 m^2) of cloth. It generally ranges between 1.5:1 and 4.0:1 for woven fabrics and ranges between 4.0:1 and 12:1 for felted fabrics for efficient collection. The capacity is determined by the amount of dust-laden air to be cleaned. In combination with the air-to-cloth ratio found to be necessary for the efficient removal of a specific dust, the capacity determines the total fabric area needed for the particular application. The pressure drop across the baghouse determines the fans required to push, or, as is more common to prevent erosion of fan blades from particulates, pull the air through the baghouse. The fan capacity will then require a certain level of power for operation of the baghouse.

The need for preventive maintenance measures is determined by consideration of the following[15]: 1) pressure drop measured by manometer, 2) velocity pressure measured by manometer and pilot tube, with the:

$$\text{Dust Velocity} = 4.005 \times 10^3 \times \sqrt{\text{Velocity Pressure}}$$

where Dust Velocity is in ft/min (0.3 m/min)

Velocity Pressure is in in. H_2O (2.54 cm H_2O)

3) ammeter readings to measure the current to each fan motor, which is proportional to the air volume through that section of the baghouse, 4) the temperature of the gas, which will endanger the fabric life if it is too high. These measurements should be taken in conjunction with weekly visual inspections of the bags for leakage or breakages. The measurements should be compared with previous ones to determine any trends, such as an increase, decrease, increasing change, or stabilization. These trends can be interpreted as to the necessity or effectiveness of various maintenance procedures.

Advantages and Disadvantages of Baghouses

The advantages of baghouses for general dust cleaning operations include the following[5,13].

1. They are efficient down to sub-micron sizes.
2. They create a positive barrier to the dust laden air not dependent on supplementary devices or materials, changing direction, or electrical charging.
3. They present no secondary pollution problem, as does a wet collector.
4. Baghouses are extremely reliable.
5. Efficiency is fairly uniform over a wide range of particle sizes.

The disadvantages of baghouses and their operation are either limitations on their application or maintenance difficulties produced by poor design. The temperature of the gas stream must be above dewpoint and less than 93.3° C

(200° F) for most natural fabrics, while some synthetic fabrics, especially Dupont "Nomex" and fiberglass can be used at temperatures up to 232.2-260° C (450-500° F). Baghouses also have the problem of fairly high pressure drops, depending on the fabric used and the design of the baghouse, thus necessitating considerable power consumption and operating expense. High moisture content of the gas is also a problem, as natural fabrics will rot at high humidities, and all fabrics tend to plug if the gas stream is very wet. Location of a broken bag can cause maintenance problems in some baghouse designs. Large space requirements can also be a limiting factor in some applications.

Baghouses are the control device most commonly used in the asbestos industry. They are used so predominantly for asbestos control because of; "their extreme efficiency for asbestos and asbestos cement dust"[1], "the toxicity of the dust, and the value of the product"[13]. Collected raw asbestos is generally recycled directly to regrading screens; however, its resale value is \$13.60-16.33/metric ton (\$15-18/ton)[3]. The application of different types of baghouses to various phases of the asbestos industry are shown in Table 2.

Baghouses for asbestos mills are frequently purchased separately, and installed in the mill building. Therefore, they have the advantage of being able to recirculate warn, heated air in the winter, and to cool by the draft created in the summer. Recirculation of baghouse air can create an OSHA problem in that plant air can contain no more than 2 fibers greater than 5 μm in length per cm^3. There is a trend at present toward modular construction of baghouses, which decreases the cost and time involved in field installation, but lose the advantages that a custom designed unit would have[4,12,17]

Table 2. FABRIC FILTER APPLICATIONS -- ASBESTOS MINING AND MANUFACTURING

Application	Type of Collector	Type of Cloth	Length of Bags cm (in.)	Diameter of Bags cm (in.)	Air:Cloth Ratio m/min (ft/min)	Expected Δp cm H_2O (in. H_2O)
Asbestos milling	Continuous	Cotton sateen	427 (168)	12.7 (5)	0.75-0.91 (2.5-3.0)	6.35-10.16 (2.5-4.0)
Asbestos ore dryers	Continuous	Orlon	427 (168)	12.7 (5)	0.75 (2.5)	3.82-5.08 (1.5-2.0)
Asbestos cement raw material handling	Continuous	Cotton sateen	320 (126)	12.7 (5)	0.75 (2.5)	7.62 (3.0)
Asbestos cement finishing machines	Intermittent	Cotton sateen	427 (168)	12.7 (5)	0.62 (2.0)	3.82-5.08 (1.5-2.0)
Textile carding	Intermittent	Cotton sateen	320-427(126-168)	20.4 (8)	1.55 (5.0)	3.82-5.08 (1.5-2.0)

Data based on several plants of Johns-Manville Corporation. Abstracted from Reference 2.

The only disadvantage of baghouses peculiar to asbestos is that the filter material and weave must be such that it is least possible for the fibers to interlace and interlock with the fabric[5]. The limitations on gas temperature and moisture content may also present problems in certain situations; however, they can usually be overcome by the proper selection of fabric and the design of the baghouse. As an example, insulated baghouses using Nomex are used on ore dryers.

An air-to-cloth ratio of 0.62-0.75:1 m/min (2.0-2.5:1 ft/min) is preferred for asbestos removal; however, a ratio of 0.91:1 m/min (3.0:1 ft/min) is more generally used, as it is more economical due to reduced space, blower, and filter bag requirements[4]. Other operating characteristics are determined by the size of the plant, the design of the particular baghouse, and the filter fabric used.

COSTS OF OPERATING AND INSTALLING CONTROL DEVICES

The economic and technical factors which determine the selection of a control device for a particular gas cleaning application are: 1) particle size, 2) pressure drop, 3) wet or dry state of gas and pollutant, 4) efficiency required, 5) temperature of gas, 6) wet or dry effluent, 7) presence of dewpoint collectors, 8) cyclic variations of volume, temperature, and concentration, 9) availability of services, i.e., water, electricity, compressed air, etc., 10) pre-filtration conditioning requirements, 11) cost of initial dust and fume containment and effluent discharge sections of the total installation, 12) corrosive conditions, 13) relative importance of capital and operating costs, 14) consequential costs from plant failure, 15) commodity values of the effluent, 16) disposal values of the effluent, 17) intermittent of continuous operation, 18) available supervisory and maintenance staff, 19) site restrictions, and 20) total gas volumetric flow[19] .

Graphs and tables of capital and operating costs versus gas volume for various types of collectors are given in numerous publications[19,20,21,22,23]. The rule-of-thumb costs for typical collectors are given in Table 3. For asbestos operations in particular, they are given in Table 4. In general, in the United Kingdom, ventilation aids add 20-37% to the cost of a new plant, the total dust extraction bill is 7% of the wages bill, and 2.7% of the total cost of production of asbestos fiber[3]. Fabric bags are responsible for 20-40% of the total equipment cost and the average bag life is 18-36 months, so that an installation operating for 10 years must be rebagged 3 to 7 times[18]. For a baghouse, the installation-to-purchase cost ratio is typically 1.8 with an average low of 1.5, high of 2.0, and an extremely high value of 5.0[22].

The maintenance costs of baghouses are dependent on

1. type of bag suspension
2. internal walkways which determine bag accessibility
3. floor plan, i.e., number of rows between walkways, which determines the reach to the furthest bag
4. external access to upper and lower levels
5. dampers and operators
6. compartment isolation, i.e., whether or not each compartment's damper has separate controls
7. the type of cleaning mechanism (In this article[14], separate reverse air fans and capacities per compartment of 0.12 for mechanical shaking, 0.39 for simple collapse, and 0.62 m^3/min of reverse air per m^2 of cloth (0.4, 1.25, and 2.0 cfm/ft^2, respectively) in the compartment are recommended.)
8. bag cleaning controls, i.e., whether there are adjustable program timers for the frequency and duration of bag cleaning and dust settling periods, pressure activated switches, or intermittent cleaning.

Table 3. RULE-OF-THUMB COSTS OF TYPICAL COLLECTORS, STANDARD MILD STEEL CONSTRUCTION

Type of Collector	Equipment Cost $/lpm ($/cfm)	Erection Cost $/lpm ($/cfm)	Yearly Maintenance and Repair Cost $/lpm ($/cfm)
Mechanical collector	$0.002-0.009 ($0.07-0.25)	$0.001-0.004 ($0.02-0.12)	$0.0002-0.001 ($0.005-0.02)
Electrostatic precipitator	$0.009-0.035 ($0.25-1.00)	$0.004-0.018 ($0.12-0.50)	$0.0004-0.002 ($0.01-0.025)
Fabric filter	$0.012-0.044 ($0.35-1.25)	$0.009-0.018 ($0.25-0.50)	$0.001 -0.003 ($0.02 -0.08)
Wet scrubber	$0.004-0.014 ($0.10-0.40)	$0.014-0.056 ($0.04-0.16)	$0.001 -0.002 ($0.02 -0.05)

Data abstracted from Reference 18.

Table 4. TYPICAL COSTS FOR THE CANADIAN ASBESTOS INDUSTRY

Type	Typical Emission Rate[1] kg/hr (lb/hr)	Cost per Process Rate cost/metric ton/hr (cost/ton/hr)	Cost per Flow Rate cost/lpm (cost/cfm)
Cyclone collector	135.0 (300)	\$ 33 (\$ 30)	\$0.003 (\$0.09)
Multiple cyclone	45.0 (100)	\$ 66 (\$ 60)	\$0.006 (\$0.18)
Wet collector	3.2 (7)	\$440 (\$400)	\$0.042 (\$1.20)
Bag filter	0.5 (1)	\$880 (\$800)	\$0.085 (\$2.40)
Electrostatic precipitator	2.7 (6)	\$440 (\$400)	\$0.035 (\$1.00)

(1) Per ton per hour processed

Data abstracted from Reference 8.

9. protection of bags by arrangement, suspension, and whether or not internal supports are required for the cleaning mechanism

10. hopper discharge valves

11. materials handling requirements[14]

Several examples of dust collection costs in the asbestos industry are cited in the literature. Johns-Manville Corporation is probably the largest asbestos manufacturer in the world. It has hundreds of fabric filters in over a hundred air and dust handling systems at a total cost of \$18 million[9]. Their largest single unit at Asbestos, Canada processes 700-800 tons of ore per hour and handles approximately 127,000 m^3/min (4.5 x 10^6 cfm) at a cost of \$8 million. Johns-Manville has stated that total installation costs range from \$70.50-\$176.00/m^3 (\$2.00-5.00/ft^3) at room temperature, though they are higher at higher temperatures[2]. Another Quebec asbestos mill cost \$1.9 million for a 19,800 m^3/min (700,000 cfm) installation[8]. An amosite mill in the United Kingdom, producing 21,768 metric ton/yr (24,000 ton/yr), has a dust control system handling 2,550 m^3/min (90,000 cfm) operating at 99.5% efficiency for particles greater than 5 μm size which cost 27.5% of the total capital cost of the plant and operates for \$195,000/yr[3]. Examples of other baghouse applications and their costs in other industries can also be found in the literature; however, their applicability to asbestos operations is only general, as the fibrous nature of asbestos creates special cleaning difficulties because of the ultra small particle size and the need for extremely high efficiencies.

SUMMARY

Baghouses are the most common control device in the asbestos industry. They are used both with and without cyclones as pre-cleaners. Baghouses are extremely efficient for the control of asbestos dust, achieving efficiencies over 99%, and have the additional advantage of recycling valuable material. An air-to-cloth ratio of 0.62-0.75:1 m/min (2.0-2.5:1 ft/min) is preferred, but a 0.91:1 m/min (3.0:1 ft/min) ratio is more common in the asbestos industry because of the saving in equipment costs. Baghouses may either be installed within the mill building with the advantage of recirculating heated air in the winter and cooling in the summer, or of separate construction. Temperature restrictions are not critical in most applications, so the fabric used is generally decided by the type of cleaning mechanism and the cost related to the bag life. Bag shape is also generally determined by baghouse design and cleaning mechanism.

The costs of a baghouse installation in the asbestos industry are widely variant, depending on the size type of plant, baghouse capacity, type of cleaning mechanism, and filter bag used. Johns-Manville, the largest asbestos manufacturer in the United States, suggests a cost of \$70.50-\$176.00/m^3 (\$2.00-5.00/ft^3) at room temperature. Other sources suggest capital costs of \$0.02-0.06/lpm (\$0.60-1.75/cfm)[18], and \$0.08/lpm (\$2.40/cfm)[8]. Annual operating costs are estimated as \$0.07-0.28/lpm (\$0.02-0.08/cfm) for maintenance and repair[18] . Annual operating costs for blower operation are highly dependent on fan efficiency and local power costs.

SECTION 5

COMPILATION OF CONTROL EQUIPMENT USER'S DATA

INTRODUCTION

Based on our user's inquiries, baghouses are the predominate method of controlling asbestos emissions. Typically, these baghouses use cotton fabric and automatic shakers. The usual capacity is 140-570 m^3/min (5,000-20,000 cfm) with an air-to-cloth ratio of less than 0.91 $m^3/min/m^2$ of cloth (3.0:1 cfm/ft^2). The time between bag cleanings is less than 4 hr. Baghouses are relatively free of operating problems. Normal installation costs ranged from $0.088-0.106 per lpm ($2.50-3.00/cfm) with operating costs ranging from $0.0018 to $0.035 per lpm per year ($0.05-1.00/cfm/yr).

SIZE AND PRODUCTS OF THE PLANTS

The listing of asbestos users from all available sources totaled 249 locations. Of these, 56 could not be contacted, 36 refused or were unable to give any information, 31 no longer use asbestos, 35 use asbestos, but have no dust collectors, 12 did not reply to written inquiries, and 79 plants gave some information about their operations and dust collection. The companies or locations which use asbestos but have no control equipment were either involved in manufacturing finished products from pre-processed asbestos of some form (88.6%), or in the sale of asbestos or processed asbestos (11.4%). The companies which no longer use asbestos had generally used very little asbestos previously and had found substitute materials due to regulatory pressures on the use or control of asbestos.

The plants which did give information did not always reply to all the questions or did not have the information that was requested. Therefore, the total number of plants reported for any given inquiry may differ by a large degree from the total number which gave some information on all inquiries.

The products manufactured by the 79 respondents are listed in Table 5. The largest number of plants manufactured either friction materials (19.0%), textiles (14.4%), floor tile (12.2%), or roof shingles (10.6%).

The size of the respondent companies, both by total employees and those in handling asbestos are shown in Table 6. On a total employee basis, 54.1% have 200 or less, while on a basis of employees handling asbestos, 65.5% have 100 or less.

The types and amounts of asbestos consumed are listed in Table 7. Chrysotile is used by 81.3% of the plants responding to this question; 50% use 907 metric tons/year (1,000 tons/yr) or less, and 31.3% use more than 4,535 metric tons/yr (5,000 tons/yr) of chrysotile.

TYPES OF CONTROL DEVICES USED

The number of plants using any type of control device and the total number of each device being used are presented in Table 8. Baghouses are used in the overwhelming majority of plants (80.0%), and also are the most popular in number of devices used (90.1%). Wet scrubbers are the second commonest used by plants and third by number; however, these devices comprise only 6.8% and 2.1% of these groups, respectively. It was also found that the scrubbers used are wet

Table 5. PRODUCT MANUFACTURED

Asbestos-Containing Product	No. of Plants Manufacturing Product	Percent
Friction materials	17	19.0
Textiles	13	14.4
Floor tile	11	12.2
Roofing shingles	10	10.6
Cement pipe	7	7.8
Gaskets	7	7.8
Paper	7	7.8
Wall board, siding, and/or plaster	6	6.7
Insulation	3	3.3
Raw asbestos	2	2.2
Asbestos cement	2	2.2
Paint, asphalt	1	1.1
Liquid filter medium	1	1.1
Industrial rubber	1	1.1
Steel mills and foundary additives and insulation	1	1.1
Chemical corrosive resistant materials	1	1.1
Total Number of Plants	90	100.0

Table 6. SIZE OF ASBESTOS MANUFACTURING PLANTS

Size Category No. of Employees	Plants with Total Employment in Indicated Size Category		Plants with the Indicated Number of Asbestos Process Employees	
	No. of Plants	% of Plants	No. of Plants	% of Plants
≤100	14	22.9	36	65.5
101- 200	19	31.2	12	21.8
201- 300	11	18.0	4	7.3
301- 400	4	6.6	1	1.8
401- 500	3	4.9	1	1.8
501- 800	4	6.6	1	1.8
801-1,000	2	3.3	----	---
1,000-1,500	1	1.6	----	---
1,501-2,500	3	4.9	----	---
Total	61	100.0	55	100.0

Table 7. TYPES OF ASBESTOS PROCESSED IN PLANTS

Type of Asbestos	Plants Using Type		Amount of Asbestos Used(1)						
			≤ 91	92-453	454- 907	908-1,361	1,362-4,513	> 4,513	metric tons/yr
	No.	Percent	≤ 100	101-500	501-1,000	1,001-1,500	1,501-5,000	> 5,000	tons/yr
Chrysotile	52	81.3	1 (6.2)	4 (25.0)	3 (18.0)	1 (6.2)	2 (12.5)	5 (31.3)	
Amosite	2	3.1	---	---	1 (100.0)	---	---	---	
Crocodolite	2	3.1	---	1 (100.0)	---	---	---	---	
Processed(2)	8	12.5	---	---	---	---	---	---	
Total	64	100.0							

(1) For those 18 plants which reported Quantity Consumed

(2) Processed asbestos includes those industries which do not use raw asbestos, but rather some pre-processed form, such as insulation, cement, or cement pipe for fabrication of end products.

Table 8. DUST CONTROL DEVICES

Control Device	Plants Using Device No.	Plants Using Device Percent	Total Devices Used No.	Total Devices Used Percent
Baghouse	72	80.0	335	90.1
Scrubber	6	6.8	8	2.1
Cyclone-baghouse combination	4	4.4	12	3.2
Cyclone	4	4.4	7	1.9
Filter systems	3	3.3	6	1.6
Scrubber-baghouse combination	1	1.1	4	1.1
Total	90	100.0	372	100.0

centrifugal scrubbers designed and utilized for the control of wet processes in plants which also have baghouses for the control of dry processes. This type of wet centrifugal scrubber has an efficiency of 98% plus and is EPA approved for wet processes.

Cyclone and cyclone-baghouse combinations are the third and fourth most common control systems. Both are used by 4.4% of the plants; however, the cyclone-baghouse combination comprises 3.2% of the total control devices, while cyclones alone comprise only 1.9%. Cyclones as the sole method of dust control in asbestos applications are rapidly declining in number. They are being replaced by baghouses, because their collection efficiencies cannot meet EPA regulations. Cyclone-baghouse or scrubber-baghouse combinations have the advantage of increased filter bag life, as the gas stream is precleaned of the larger, abrasive particles before it reaches the bags.

Central vacuum filter systems are generally used in fabricating operations on asbestos products such as brake linings, asbestos cement pipe, or asbestos insulation. In design, these systems are often similar to a small-scale baghouse.

WASTE DISPOSAL AND EFFICIENCY TESTING

The methods of waste disposal and their relative usages are given in Table 9. The most prevalent methods of waste disposal are reuse (39.2%) and dumping (37.0%). Reuse is most common in those industries which use raw asbestos as the raw material and use separate dust collection systems for it, e.g., cement pipe and insulation manufacturing.

Of the plants which responded to whether or not they had conducted efficiency tests, 62.8% replied positively, i.e., that some kind of testing, including OSHA testing, had

Table 9. METHOD OF WASTE DISPOSAL

Method	No. of Plants Using Method	Percent of Total
Reuse	38	39.2
Dump	36	37.0
Landfill	13	13.4
Sell	5	5.2
Store	3	3.1
Wet slurry*	2	2.1
Total	97	100.0

* Form of Waste Ultimate Disposal not specified.

been done, while 37.2% replied negatively. However, of those 37.2%, 7.7% of the total stated that they accepted the manufacturer's values. Very few (19) companies were willing and able to give numerical values for efficiency. Of those reporting, 73.7% had mass collection efficiencies greater than 99.0%.

DETAILS OF BAGHOUSE USE

As baghouses are the predominant means of asbestos control, a more detailed inquiry was made as to the sizes and characteristics of those used. The major manufacturers of baghouses used in the asbestos industry are Wheelabrator-Frye, the Pangborn Division of Carborundum Corporation, and W.W. Sly. Their products are used in 21.3, 13.9, and 10.6% of the plants reporting, and amount to 27.2, 13.8, and 14.2% of the total number of baghouses reported, respectively. The complete listing of manufacturers is presented in Table 10.

The gas flow capacities of both the plants and the baghouses can be found in Table 11. Of the plants replying, 61.9% had total flows of 2,830 m^3/min (100,000 cfm) or greater; however, 87.6% of the baghouses in the plants are 577 m^3/min (20,000 cfm) or less and 98.5% of the plants have baghouses within this range. The air-to-cloth ratios in m^3/min of gas flow:square meter of cloth area (cfm of gas:ft^2 of cloth) of 0.75:1 (2.5:1) or less and from 0.75:1 to 0.91:1 (2.5-3.0:1) are used by 28.6% of the plants. While 40.0% of the baghouses have ratios of 0.75:1 (2.5:1) or less, 20.9% have 0.75-0.91:1 (2.5-3.0:1) and 30.9% have 1.24-3.10:1 (4.0-10.0:1). Generally, the ratios of 0.91:1 (3.0:1) or less are on mechanically shaken units, while those with ratios of 1.24:1 (4.0:1) or greater are on reverse jet units. The air-to-cloth ratios used are given in Table 12.

Table 10. BAGHOUSE MANUFACTURERS

Manufacturer	Plants Using Product		Baghouses in Operation	
	No.	Percent	No.	Percent
Wheelabrator-Frye	26	21.2	95	27.2
Pangborn Div., Carborundum Corp.	17	13.9	48	13.8
W.W. Sly	13	10.6	50	14.2
Industrial Clean Air (Rees Blowpipe)	9	7.4	17	4.9
MikroPul	6	4.9	17	4.9
Torit	4	3.3	12	3.4
Flex Kleen, Sub. Research Cottrell	3	2.3	10	2.9
American Air Filter	3	2.3	8	2.3
Home/Custom Made	3	2.3	6	1.7
J.A. Kleissler	3	2.3	6	1.7
Dravo	3	2.3	5	1.4
Amerjet	3	2.3	5	1.4
Parsons	2	1.6	8	2.3
Air Purification Methods	2	1.6	4	1.1
Ducon	2	1.6	4	1.1
Johnson-March Corp.	2	1.6	3	0.9
Western Precipitation, Sub. Joy Mfg.	1	0.8	5	1.4
Cincinnati	1	0.8	5	1.4
Mine Safety Appliance	1	0.8	4	1.1
Buffalo Forge	1	0.8	4	1.1
Northern Blower	1	0.8	4	1.1
Tenner & Hans	1	0.8	5	1.4
Aget	1	0.8	3	0.9
Trybourns	1	0.8	2	0.6
Walch	1	0.8	2	0.6
Dynavane	1	0.8	2	0.6
Farr	1	0.8	2	0.6
Wm. J. Schmitt	1	0.8	2	0.6
Porter	1	0.8	1	0.3
Kurt & Bloom Mfg. Co.	1	0.8	1	0.3
Hoffman Air & Filtration	1	0.8	1	0.3
Ruemelin	1	0.8	1	0.3
Carter Day Div., Hart-Carter Co.	1	0.8	1	0.3
Lorbrow	1	0.8	1	0.3
John Wood	1	0.8	1	0.3
Tek Air	1	0.8	1	0.3
Wiedenmann	1	0.8	1	0.3
Tongeren	1	0.8	1	0.3
Fuller	1	0.8	1	0.3
Total	124	99.9	349	99.9

Table 11. CAPACITY OF DUST COLLECTION SYSTEM

Capacity		Plants Having Stated Total Capacity		Baghouses in Plants Having Stated Total Capacity		Plants Having Baghouses Within Stated Range of Capacity	
m^3/min	cfm	No.	Percent	No.	Percent	No.	Percent
$\leq$ 142	< 5,000	1	4.8	19	21.6	5	17.8
143- 283	5,001- 10,000	1	4.8	27	30.7	9	32.2
284- 566	10,001- 20,000	---	----	31	35.3	8	28.5
567- 849	20,001- 30,000	---	----	4	4.5	3	10.7
850-1,416	30,001- 50,000	4	19.0	2	2.3	1	3.6
1,417-2,832	50,001-100,000	2	9.5	4	4.5	1	3.6
2,833-5,663	100,001-200,000	8	38.2	1	1.1	1	3.6
> 5,663	>200,000	5	23.7	---	----	---	----
	Total	21	100.0	88	100.0	28	100.0

Table 12. AIR-TO-CLOTH RATIO

Air-to-Cloth Ratio		Plants Having Ratio		Baghouses Having Ratio	
m/min	ft/min	No.	Percent	No.	Percent
≤ 0.62:1	≤ 2.0:1	3	14.3	22	20.0
0.63-0.75:1	2.1- 2.5:1	3	14.3	22	20.0
0.76-0.91:1	2.6- 3.0:1	6	28.6	23	20.9
0.92-1.24:1	3.1- 4.0:1	2	9.5	9	8.2
1.25-3.10:1	4.1-10.0:1	7	33.3	34	30.9
	Total	21	100.0	110	100.0

The fabric used (see Table 13) in the majority (72.2%) of baghouses in the asbestos industry is cotton. The automatic shaker type of cleaning mechanism is used by 59.0% of the plants and in 63.3% of the baghouses. The other less popular cleaning mechanisms used are listed in Table 14. The cleaning cycle used (see Table 15) is less than 15 min., from ½ to 1½ hr, and from 1½ to 4 hr in 25.0, 29.5, and 25% of the plants and 19.8, 31.2, and 30.2% of the baghouses, respectively. The pressure drop across the baghouses is 7.6 cm (3 in.) of water or less in 50% of the plants and 57.8% of the baghouses. The breakdown of pressure drop is given in Table 16.

Seventy-two plants responded to the question on baghouse operating problems, and 63 said they had none. Shaker mechanisms and breaking bags were the major problem, each being reported by 4.2% of the plants responding. Overloading, freezing bags, and steam were each reported by one plant (1.4%).

COST OF EQUIPMENT

The cost of installing or operating a baghouse is difficult to ascertain, as most companies do not give out such information or do not have it readily available. Manufacturers usually bid on a contract to supply control equipment. They claim that each unit is different with few standard parts. Therefore, they fabricate individual units to suit the particular plant. This explains to some extent their reluctance to quote a figure. In general, from user's data, the cost of purchasing a baghouse is in the range of 7¢-10.5¢/lpm ($2.50-3.00/cfm). However, costs were reported as low as 3.5¢/lpm ($1.00/cfm), and as high as 60¢/lpm ($17.00/cfm). Total annual operating costs, which includes the costs for power and maintenance, ranged from 0.175¢-3.5¢/lpm/yr ($0.05-1.00/cfm/yr) with no trends within that range clear from the data available.

Table 13. BAG FABRIC

Fabric	Plant Using Fabric		Baghouses Using Fabric		Bag Cleaning Mechanism Used With Type of Fabric, No. (%) of Baghouses			
	No.	Percent	No.	Percent	Hand Shaker	Automatic Shaker	Reverse Jet	Pulse Jet
Cotton	36	62.3	164	72.2	27 (16.4)	125 (76.8)	10 (6.7)	2 (1.2)
Dacron	8	13.8	31	13.7		23 (74.2)	3 (9.7)	5 (16.1)
Polyester	5	8.6	15	6.6		---	5 (33.3)	10 (66.7)
Canvas	2	3.4	4	1.8		4 (100.0)	---	---
Wool	2	3.4	2	0.9		2 (100.0)	---	---
Nylon	1	1.7	4	1.8		4 (100.0)	---	---
Orlon	1	1.7	3	1.3		3 (100.0)	---	---
Polyprolene felt	1	1.7	3	1.3		---	---	3 (100.0)
Polyphrone felt	1	1.7	1	0.4		---	1 (100.0)	---
Burlap	1	1.7	---	----				
Total	58	100.0	227	100.0				

Table 14. BAG CLEANING MECHANISM

Cleaning Mechanism	Plants Using Mechanism		Baghouses Using Mechanism	
	No.	Percent	No.	Percent
Automatic shaker	39	59.0	160	63.3
Pulse jet	10	15.2	28	11.0
Reverse jet	9	13.6	33	13.1
Hand shaker	8	12.2	32	12.6
Total	66	100.0	253	100.0

Table 15. BAG CLEANING CYCLE

Cleaning Cycle	Plants Using Cycle		Baghouses Using Cycle		Bag Cleaning Mechanism Used No. (%)			
	No.	Percent	No.	Percent	Hand Shaker	Automatic Shaker	Reverse Jet	Pulse Jet
$\Delta t \leq 5$ min	3	12.50	10	10.4	8 (80.0)	2 (20.0)	---	---
5 min $< \Delta t \leq 15$ min	3	12.50	9	9.4	--	2 (22.2)	---	7 (77.8)
15 min $< \Delta t \leq 45$ min	2	8.25	8	8.3	--	6 (75.0)	---	2 (25.0)
45 min $< \Delta t \leq 1$ hr	3	12.50	12	12.5	--	12 (100.0)	---	---
1 hr $< \Delta t \leq 1\frac{1}{2}$ hr	2	8.25	10	10.4	--	10 (100.0)	---	---
$1\frac{1}{2}$ hr $< \Delta t \leq 4$ hr	6	25.00	29	30.2	--	29 (100.0)	---	---
4 hr $< \Delta t \leq 1$ day	3	12.50	16	16.7	12 (75.0)	4 (25.0)	---	---
Intermittent	2	8.25	2	2.1	2 (100.0)	--	---	---
Total	24	100.00	96	100.0				

Δt = time between cleaning cycles

Table 16. PRESSURE DROP ACROSS BAGS

Pressure Drop cm (in.) H_2O	Plants Having Δp		Baghouses With Δp		Bag Cleaning Mechanism Used No. (%)			
	No.	Percent	No.	Percent	Hand Shaker	Automatic Shaker	Reverse Jet	Pulse Jet
$\Delta p \leq 2.54$ (1)	2	10.0	2	2.0	--	2 (100.0)	---	---
2.54 (1) < $\Delta p \leq 5.08$ (2)	3	15.0	40	39.2	7 (17.5)	16 (40.0)	10 (25.0)	7 (17.5)
5.08 (2) < $\Delta p \leq 7.62$ (3)	5	25.0	17	16.6	--	11 (64.7)	4 (23.5)	2 (11.8)
7.62 (3) < $\Delta p \leq 10.2$ (4)	10	50.0	43	42.2	7 (16.3)	26 (60.4)	4 (9.3)	6 (14.0)
Total	20	100.0	102	100.0				

SECTION 6

EMISSION DATA COLLECTION AND ANALYSIS

INTRODUCTION

Emissions data was collected from baghouses at five locations. They were chosen because of the nature of the asbestos processing undertaken. They include: two asbestos refining mills dealing with natural asbestos, two asbestos cement product plants where the asbestos was bound into the product, and an asbestos textile plant where the product is loosely bound. In all of the locations, chrysotile asbestos was used exclusively.

Membrane filter samples were taken both upstream and downstream of the baghouse. Two types of samples were taken. Samples were taken over a four hour period to obtain mass efficiency data. To obtain size efficiency data, samples were taken for short time periods of approximately 5 minutes on the inlet side, and 30 minutes on the outlet side. These filter samples were then examined by optical and electron microscope, and the number and size distribution of the fibers was noted.

The purpose of the emission testing was to provide preliminary factual data on the extent of the emissions from baghouses. It was to provide a quick answer on the question of whether a study on improving the efficiency of baghouses was warranted, and to provide base data from which the ambient air exposure levels in the vicinity of the plant could be calculated.

GENERAL SAMPLING PROCEDURES

The sampling scheme used for this study followed the EPA method as detailed in the Federal Register 36-247. The general outline is given here, specific details of the procedures at each site will be given separately in the follwoing text.

Sampling points in the ductwork were selected in regions where the most stable flow patterns existed. The ports were located, where possible, eight to ten diameters downstream and three to five diameters upstream from any bends, elbows, junctions, or other constrictions in the stack or duct.

The velocity profile in the stack or duct was measured by means of an S-type pitot tube. The pitot tube was traversed across the stack or duct, the gas velocity was determined at the center of each equal area zone. The average velocity was then determined by averaging the velocities in all of the zones from:

$$\overline{V}_s = \frac{\Sigma_i (V_i)}{N}$$

where $\overline{V}_s$ = Average velocity

V_i = Velocity at one point

N = Number of points

Two standard EPA Method 5 isokinetic sampling systems (as shown in Figure 1) were used to collect the air samples from the upstream and downstream ductworks of the baghouse. The sampling probes and nozzles were fabricated from stainless steel. The probes were 1.27 cm (0.5 in.) I.D. and 107 cm (42 in.) long, and the nozzles were 0.63 cm (0.25 in.) I.D.

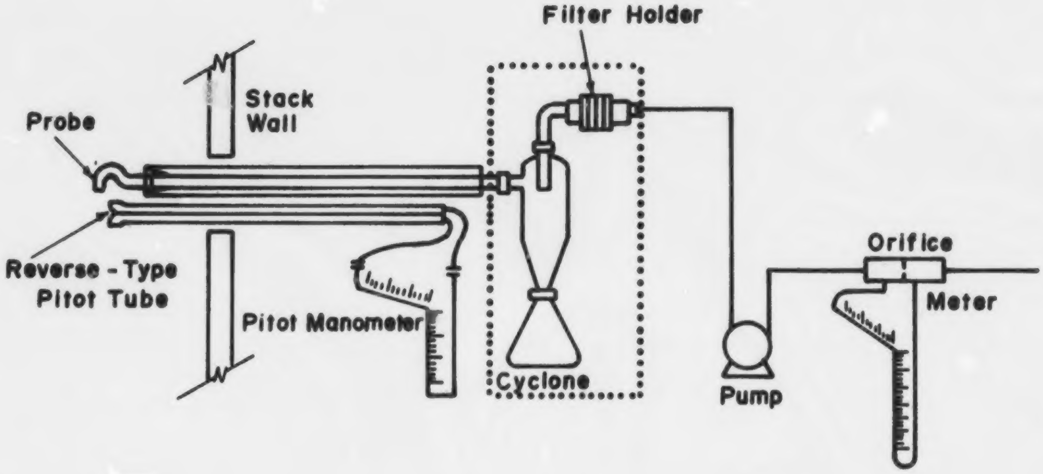
Filter Holder
Stack Wall
Probe
Reverse - Type Pitot Tube
Pitot Manometer
Cyclone
Orifice
Meter
Pump

Figure 1. Sampling arrangement

On the upstream side of the baghouse, samples were drawn through a cyclone followed by a 10.2 cm (4 in.) membrane filter (Millipore) of 0.8 μm pore size. On the downstream side, no cyclone was used; the air stream was lead directly to the membrane filter. After sampling, the filters were placed into marked plastic folders. Material adhering to the inside of the probe and tube was washed into the cyclone sample collector using acetone. The collector was then marked and sealed.

In some instances, it was not possible to collect samples by the isokinetic stack sampling method. This was because there was no suitable length of ducting or stack from which valid samples could be collected. Here, a high volume sampler was used with a 20.3 x 25.4 cm (8 x 10 in.) membrane filter. Some error would be introduced by using this method. However, because of the small size of the particles passing through the baghouse, the error would be small. When this method was used, the sampler was located inside the baghouse, close to the exiting point.

SPECIFIC SITE INFORMATION

Johns-Manville, Asbestos Cement Pipe Plant, Waukegan, Illinois

Plant Details -

Dust Source: Lathes for cutting and trimming asbestos cement pipes containing asbestos, cement, and sand.

Baghouse: Parsons unit, installed December, 1972
Four compartments
200 bags per compartment, total 800 bags
Capacity: 283 m^3/min (10,000 cfm) per compartment
1,132 m^3/min (40,000 cfm) total
Operating temperature: 20.5° C (69° F)
Pressure drop: 15.2 cm (6 in.) H_2O
Air-to-cloth ratio: 2:1

Bags: Cotton sateen
12.7 cm (5 in.) diameter
3.05 in. (10 ft) length
Total area per bag: 1.22 m^2 (13.1 ft^2)
Permeability: 4.57 ± 1.52 m/min at 1.27 cm H_2O
(15 ± 5 cfm/min at 0.5 in. H_2O)
Bag life: 2-3 years

Baghouse Cleaning: Mechanical shake
Each compartment is shaken for 2 minutes every 30 minutes
A compartment is shut off while shaken; there are always 3 compartments on stream.
Collected waste is taken to dump.

Baghouse Effluent: vented to the exterior through a short stack about 3 m (10 ft) tall and a total of 10 m (30 ft) above the ground

Sampling Procedure -

Upstream samples were collected from a 86 cm (34 in.) circular duct approximately 5.5 m (18 ft) from the floor. A platform was erected to reach the duct at a point more than eight diameters from any obstruction or bend in the ductwork. Two sampling ports, one entering the duct vertically, the other horizontally, were cut into the duct; each was approximately 5 by 7 cm (2 by 3 in.).

Linear gas velocities in the duct were measured using an S-type pitot tube. The duct was traversed both vertically and horizontally. The pressure drop across the manometer and the stack temperature were measured at distances of 10, 25, 41, 56, 71, and 87 cm (4, 10, 16, 22, 28, and 34 in.) inside the duct. The average duct velocity calculated from the vertical traverse was found to be 1,021 m/min (3,354 fpm) and from the horizontal traverse 1,032 m/min (3,386 fpm).

Dust samples were collected isokinetically on Millipore membrane filters of 0.8 μm pore size. To obtain fiber size distribution data, samples were collected with particle loadings such that the determination could be made by direct observation of the filter by either optical or electron microscopy. The time required to obtain ideal loading, that is, with the particles on the filter evenly distributed without touching, was not known. For this reason, samples were collected for times of 0.25, 15, and 30 minutes. The samples were removed isokinetically from a single sampling point 76 cm (30 in.) vertically inside the duct. At this point, the linear velocity was almost identical to the average velocity. Samples for mass efficiency measurement were collected at each of the traverse points for a period of 5 minutes. The entire sampling sequence was distributed over a 3½ hour time period.

Downstream samples were collected from a 81 by 107 cm (32 by 42 in.) rectangular stack. A platform was constructed inside the building about 8 m (25 ft) from the floor and 1.7 m (5 ft) from the roof. Three equally spaced sampling ports were cut into the 81 cm (32 in.) face of the duct at a distance of 2.5 m (8 ft) from the baghouse fan, which was located in the stack between the baghouse and the louvred exit on the roof. This sampling point was unsatisfactory because of its close proximity to the fan, but it was the only practical point to erect a platform within the constraints of the plant layout.

Linear gas velocities were measured by traversing the duct through each of the ports at depths of 10, 25, 41, 56, 71, 87, and 102 cm (4, 10, 16, 22, 28, 34, and 40 in.). The three ports gave average velocities of 1,083 m/min (3,555 fpm), 1,113 m/min (3,654 fpm) and 1,175 m/min (3,856 fpm), respectively.

Samples for microscopic examination of the fiber size distribution were taken from the central port at a depth of 33 cm (13 in.). The samples were collected for time periods of 5, 15, and 30 minutes.

To obtain mass efficiency data, samples were collected from each port at each traverse point for a period of 10 minutes. The upstream and downstream sampling was performed within the same 3½ hour total sampling time period.

Raybestos, Asbestos Textile Plant, Marshville, North Carolina

Plant Details -

Dust Source: Carding machine which combs raw asbestos fiber into a roughly parallel array prior to spinning.

Baghouse: Wheelabrator model 112, installed in 1953
Single compartment, 304 bags
Capacity: 473 m^3/min (16,700 cfm)
Operating temperature: 26.7° C (80° F)
Pressure drop: 5.59 cm (2.2 in.) H_2O
Air-to-cloth ratio: 3:1

Bags: Cotton sateen
20.3 cm (8 in.) diameter
2.82 m (9.25 ft) length
Total area per bag: 1.80 m^2 (19.4 ft^2)
Permeability: 4.57 ± 1.52 m/min at 1.27 cm H_2O
(15.0 ± 5.0 cfm/min at 0.5 in. H_2O)
Bag life: 5 years

Baghouse Cleaning: Mechanical shake
At the finish of each shift, the cake from the bags is shaken into an empty hopper - this material is put in polythene bags and dumped at a city site.
Three times during each shift the material collecting in the baghouse hopper (without shaking) is collected and recycled.

Baghouse Effluent: Effluent is either recirculated to conserve heat, or vented to the outside air, depending on ambient temperature conditions. A very short (1 m) stack is used to vent the effluent to the outside air.

Sampling Procedures -

Upstream samples were collected from a 76 cm (30 in.) diameter duct. The only convenient sampling point was about 3 duct diameters from the baghouse and 5 duct diameters from a bend. Because of the very thick duct walls and the inaccessibility of the duct, only one sampling port, which allowed a horizontal traverse to be made, was used. Linear gas velocities were measured at distances into the duct of: 2.5, 5.1, 7.6, 11.0, 15.0, 20.0, 29.0, 48.0, 56.0, 61.0, 69, 71, and 74 cm (1, 2, 3, 4.4, 6, 8, 11, 19, 22, 24, 25, 27, 28, and 29 in.). The average gas velocity was found to be 956 m/min (2,915 fpm).

Dust samples were collected isokinetically on Millipore membrane filters of 0.8 μm pore size. Samples for the determination of fiber size distribution were taken from a point 30.5 cm (12 in.) into the duct. Three sampling periods of 0.25, 1, and 5 minutes were utilized to obtain three filters with different loading levels. The filter with the most even loading was to be used for the fiber count. To determine the mass loading, samples were removed isokinetically for five minutes at each traverse point. Two traverses were made over a total time period of about 6 hours.

Downstream samples were taken from a 99 by 46 cm (39 by 18 in.) rectangular duct. A sampling port was cut into the 46 cm face of the duct well clear of any obstruction or bend. Only one port was cut because of the thick walls of the duct, which made it a difficult task. Linear gas velocities were measured at distances into the duct of 7.6, 15, 23, 30, 38, 46, 53, 61, 69, 76, 84, and 91 cm (3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36, and 39 in.). The average velocity was found to be 676 m/min (2,062 fpm).

Dust samples were collected isokinetically from the duct on 0.8 μm pore size Millipore membrane filters. Samples for fiber size distribution determination were collected at a point 61 cm (24 in.) into the duct for time periods of 5, 15, and 30 minutes. Samples for mass loading determination were collected by traversing the duct and collecting a sample for 10 minutes at each traverse point. The entire sampling sequence was spread over a 6 hour time period. Both upstream and downstream samples were collected over the same 6 hour time period.

Johns-Manville, Asbestos Cement Pipe Plant, Denison, Texas

Plant Details -

Dust Source: Lathes for cutting and trimming asbestos cement pipes containing asbestos, cement, and sand.

Baghouse: Wheelabrator Model 2b
Single compartment, 640 bags
Capacity: 736 m^3/min (26,000 cfm)
Operating temperature: 20.5° C (69° F)
Pressure drop: 14.5 cm (5.7 in.) H_2O
Air-to-cloth ratio: 3:1

Bags: Cotton sateen
12.7 cm (5 in.) diameter
3.18 m (10.4 ft) long
Total area per bag: 1.27 m^2 (13.6 ft^2)
Permeability: 4.57 ± 1.52 m/min at 1.27 cm H_2O
(15.0 ± 5.0 cfm/min at 0.5 in. H_2O)
Bag life: 1 year

Baghouse Cleaning: Mechanical shake, manually started at shift breaks and changes.
Waste is taken to plant dump.

Sampling Procedure -

Upstream samples were collected from a 80 cm (32 in.) diameter duct. A sampling location greater than eight diameters from any bend or flow disturbance was selected. A platform approximately 5 m (15 ft) high was erected to reach the two sampling ports which were cut into the duct to allow both vertical and horizontal duct traverses. Linear gas velocities were measured at distances into the duct of 1.7, 5.3, 9.7, 14.5, 20, 29, 43, 53, 67, 72, 76, and 80 cm (0.67, 2.1, 3.8, 5.7, 8.0, 11.4, 16.9, 20.8, 26.3, 28.2, 29.9, and 31.3 in.) in both a vertical and horizontal direction. The average gas velocities were found to be 1,510 m/min (4,605 fpm) from the vertical traverse and 1,539 m/min (4,694 fpm) from the horizontal traverse.

Dust samples were collected isokinetically on Millipore membrane filters of 0.8 μm pore size. Samples for the determination of fiber size distribution were taken from a point 46 cm (18 in.) inside the duct vertically from the lower port. Samples were collected for 0.5, 1, and 5 minutes to obtain samples with different loading levels. To obtain information for the determination of the mass loading, samples were taken at each traverse point in both the vertical and horizontal ducts for a period of 5 minutes. Samples were collected over a total time period of 5 hr 7 min.

Downstream samples were collected using a high volume sampler with an 0.8 μm pore size Millipore membrane filter, located within the baghouse close to the exit. The sampler was mounted on clamps such that the membrane face was presented face-on to the direction of the air flow. A high volume sampler was used because the very short stack between the fan and the louvred roof exhaust exit (about 1 m) presented no acceptable sampling point. Samples were collected for fiber size distribution determination for periods of

5, 15, and 30 minutes to obtain samples with different loading levels. Samples for mass loading determination were collected for 5 hr 7 min. Both the upstream and downstream samples were collected over the same 5 hr 7 min time period.

Johns-Manville, Asbestos Ore Mill, Asbestos, Canada

Plant Details -

Dust Source: Fiber screening and air aspiration system.

Baghouse: Wheelabrator, special design
One compartment, 79,200 bags
Capacity: 127,000 m^3/min (4,500,000 cfm)
Operating temperature: 21.1° C (70° F)
Pressure drop: 7.62 cm (3 in.) H_2O
Air-to-cloth ratio: 3:1

Bags: Cotton sateen
12.7 cm (5 in.) diameter
4.27 m (14 ft) length
Total area per bag: 1.70 m^2 (18.3 ft^2)
Permeability: 7.62 m/min at 1.27 cm H_2O
(25 cfm/min at 0.5 in. H_2O)
Bag life: 6-10 years

Baghouse Cleaning: Mechanical shake
2 minute shake cycle every 30 minutes
Bags are shaken in groups of 7,200 bags
Collected dust is recycled

Cyclone: Cyclone is used as a pre-cleaner
Unit is 2.44 m (8 ft) in diameter
Capacity: 424 m^3/min (15,000 cfm)
Inlet velocity: 1,219 m/min (4,000 fpm)
Exit velocity: 914 m/min (3,000 fpm)
Claimed mass efficiency is 98.5% for 30-500 μm dust at 251 m^3/min (9,100 cfm)

Baghouse Effluent: recirculated to plant for most of the year, vented outside during warm weather.

Sampling Procedure -

Upstream samples were collected from a 38 cm (15 in.) duct leading to the cyclone. It would have been preferable to sample in the duct separating the cyclone and baghouse, but it was inaccessible and had a very short (less than 1 m) connecting duct. Two identical ducts lead to the cyclone from the plant. The ducts brought air from identical operations in the plant and should have identical dust loadings. Therefore, only one duct was sampled.

The dust loading within the duct was very high and quickly blocked the sampling probe and pitot tube. The average duct velocity was estimated to be about 665 m/min (2,618 ft/min). Single point samples were taken from a point 30 cm (12 in.) into the duct. Samples were collected under isokinetic conditions until signs of blocking occurred (as observed by sudden fluctuations on the manometer). Four samples of 1.4, 1.7, 2.8, and 3.5 liters were collected.

Downstream samples were collected on a high volume sampler located within the baghouse between the sets of bags. The baghouse forms the complete top floor of the 14 story building and air is generally recirculated from the baghouse area to the plant by means of blowers. In exceptionally warm weather, the air is vented directly out through louvres in the side of the baghouse. There was no stack.

Samples for fiber size distribution determination were collected for 5 and 30 minutes to obtain a loading range. Samples for mass loading determination were collected for 5 hr.

GAF, Asbestos Ore Mill, Eden Mills, Vermont

Plant Details -

Dust Source: Fiber screening and air aspiration system.

Baghouse: Wheelabrator, Model B-607, Series VIII
8 compartments
336 bags per compartment, 2,688 bags total
Capacity: 8,490 m^3/min (300,000 cfm)
Operating temperature: 21.1° C (70° F)
Pressure drop: 10.2 cm (4 in.) H_2O
Air-to-cloth ratio: 3.2:1

Bags: Cotton sateen
20.3 cm (8 in.) diameter
5.3 m (17.5 ft) length
Total area per bag: 3.22 m^2 (35 ft^2)
Permeability: 4.88-6.10 m/min at 1.27 cm H_2O
(16-20 cfm/min at 0.5 in. H_2O)
Bag life: 5 years

Baghouse Cleaning: Mechanical shake
2 minute shake cycle every 30 minutes, one compartment at a time
Dust is recycled.

Baghouse Effluent: Baghouse is not enclosed; therefore, air always diffuses back into the plant.

Cyclone: Cyclone is used as a pre-cleaner.
Unit is 3 m (9.8 ft) in diameter.

Sampling Procedure -

Upstream samples were collected from a 76 cm (30 in.) duct leading from the cyclone to the baghouse. The duct was short (about 3 m overall) and the only accessible section was about 1 m from the cyclone. Two sampling ports, at right angles to each other, were cut into the angled duct. Linear gas velocities were measured at distances into the duct of 2.5, 5.0, 10, 15, 20, 25, 30, 36, 41, 46, 51, 56, 61, 66, 71, and 76 cm (1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, and 30 in.) from both sampling ports. The average gas velocity was found to be 1,330 m/min (4,364 fpm).

Dust samples were collected isokinetically on Millipore membrane filters of 0.8 μm pore size. Samples for the determination of fiber size distribution were collected from a point 30 cm (12 in.) into the duct for time periods of 1, 5 and 30 seconds to obtain samples at different loading levels. A sample for the determination of mass loading was obtained by sampling at each traverse point for 5 minutes over a total time period of 6 hr.

Downstream samples were collected using a high volume sampler located within the central part of the baghouse. The baghouse had no stack air being allowed to diffuse into the plant from the open baghouse.

Samples for the determination of fiber size distribution were collected for time periods of 10, 30, and 60 minutes to obtain samples with differing loading characteristics. The mass loading was determined by collecting a single sample for a time period of 6 hr. Both upstream and downstream samples were collected over the same time period.

SAMPLE ANALYSIS

Introduction

The mass efficiency and the efficiency in terms of fiber size removal were measured at each of the five sites which were sampled. The mass efficiency was found by weighing the quantity of material collected for a given volume of air, before and after the baghouse. Fractional efficiency was determined by comparing the size frequency of fibers before and after the baghouse.

In determining the mass efficiency of the baghouse, it should be noted that the measured efficiency includes non-asbestos as well as asbestos material. No attempt was made to analyze the filters to determine the asbestos content before and after the filter to see if there is a change in the composition.

The fiber counts were made with the criteria that all particles having a greater than 3:1 aspect ratio were fibers. The assumption was made that all fibrous particles coming from an asbestos plant were asbestos. Spot checks on fibers were made, and the selected area diffraction pattern was found to be characteristic of chrysotile asbestos. Thus, the assumption was deemed valid.

Mass Efficiency

The mass efficiency was found by accurately weighing the samples collected from before and after the baghouse. The filters were weighed on electronic balances at a sensitivity of ± 0.1 mg. On the upstream side, the dust deposited in the probe, the sampling train, and the cyclone was washed with water into a weighed sampling bottle. It was then dried in vacuum oven at 110° C, cooled, and reweighed. From these weights, the mass efficiency was calculated.

Fiber Counting

Optical microscope analysis was performed using the method described in the NIOSH criteria document on asbestos (HSM 72-10267). A portion of the membrane filter was mounted on a slide. Using a 1:1 solution of dimethyl phthalate and diethyl oxalate, the filter was allowed to clear. A clean cover slip was placed on top of the sample and the fiber concentration determined. The light microscope used was equipped with phase-contrast and polarized light. The objective lens of 4mm resulted in a total magnification of 500X. From randomly chosen fields, the number of fields for a total count of 100 fibers was noted (with a minimum of 20 fields observed), or, 100 fields were observed when the distribution was sparse.

For the electron microscope analysis, a circle of the sample filter 3.5 mm in diameter was cut. This piece of filter was placed on top of a carbon-coated 100 mesh electron microscope grid. The grid with the filter on it was placed in a condensation washer using acetone as a solvent. The filter medium was dissolved away by the acetone, depositing the fibers of the sample undisturbed on the carbon substrate of the grid. The specimen was then counted on a Hitachi HU-11 transmission electron microscope at the magnification of 16,364X.

The optical microscope analysis enumerated the fibers greater than 5 μm in length and a minimum diameter of 0.5 μm. The electron microscope analysis counted fibers down to 0.06 μm in length and 0.020 μm in diameter.

The NIOSH document on asbestos cited the above states that the fiber counts follow a Poisson distribution. The standard deviation for a count of 100 fields is $\sqrt{100}$, or 10 fibers or ± 10%. To keep the statistical error at the 95% confidence level, approximately two standard deviations must be considered. The uncertainty in the counts is then ± 20%.

Calculation of Fiber Numbers

To relate the number of fibers counted to the asbestos concentration in the air, the following equation was used:

$$\frac{\text{no. of fibers}}{\text{m}^3 \text{ of air}} = \left(\frac{\text{no. of fibers counted}}{\text{no. of fields}}\right) \times \left(\frac{\text{effective filter area, cm}^2}{\text{area of microscope's field of view, cm}^2}\right) \times \left(\text{volume of air sampled, m}^3\right)^{-1}$$

Effective filter area = 81.7 cm^2 for 4 in. filter

Effective filter area = 63.2 cm^2 for 4 in. hi-vol filter

Effective filter area = 426.4 cm^2 for 8 in. x 10 in. hi-vol filter

Area of field of view = 6.514×10^{-4} cm^2 for optical microscope (500X)

Area of field of view = 1.344×10^{-7} cm^2 for electron microscope (16,364X)

Efficiency Calculation

To calculate the efficiencies, both by mass and by number, the following relationships were used:

Mass Efficiency (%) =

$$100\left[1 - \frac{\text{mass in a given volume of air after the baghouse}}{\text{mass in the same volume of air before the baghouse}}\right]$$

Number Efficiency (%) =

$$100\left[1 - \frac{\text{no. of fibers per cubic meter after the baghouse}}{\text{no. of fibers per cubic meter before the baghouse}}\right]$$

RESULTS OF THE ASBESTOS SAMPLING STUDIES

The results of the sampling study are summarized in the following tables. Table 17 gives the details of the samples and the sampling conditions at each of the five locations. In Table 18, the mass efficiencies at each of the five baghouses are given. The total number of fibers, in both the optical and electron microscope size ranges, for the upstream and downstream sides of the baghouses are given in Table 19. The distribution of the fibers in the optical microscope size range (1.5-30.0 μm) is presented in Table 20. In Table 21, the size distribution of the fibers in the electron microscope size range (0.06-1.50 μm) is given.

DISCUSSION OF THE RESULTS

The mass efficiency of the baghouses tested was shown to be extremely high and in all instances was greater than 99.99%. A high mass efficiency had been anticipated, and these figures are in agreement with the very limited data which is available in the literature as reported earlier in the text.

The information gained from this study on the number of asbestos fibers emitted from a baghouse exhibiting a high mass

Table 17. SAMPLES AND SAMPLING CONDITIONS

Sampling Site	Sampling Location	Average Linear Velocity, m/min	Sampling Time	Volume Sampled (m^3)	Filter Size and Collection Method (all filters 0.8 µm membrane)	Sampling Purpose	Filter No.
Waukegan, Illinois	Upstream	1,026	4 min 25 sec		All 10 cm diameter. Isokinetic	Size	10
	Upstream	1,026	1 minute			Size	9
	Upstream	1,026	15 seconds			Size	2
	Downstream	1,098	5 minutes			Size	5
	Downstream	1,098	15 minutes			Size	7
	Downstream	1,098	27 minutes			Size	3
	Upstream	1,026	1 hr (over 3½ hr)	1.75		Mass	11
	Downstream	1,098	3½ hours	12.98		Mass	12
Marshville, North Carolina	Upstream	3,410	5 minutes		All 10 cm diameter. Isokinetic	Size	15
	Upstream	3,410	1 minute			Size	16
	Upstream	3,410	15 seconds	2.83×10^{-3}		Size	17
	Downstream	3,400	5 minutes	5.94×10^{-2}		Size	18
	Downstream	3,400	15 minutes	4.42×10^{-1}		Size	19
	Downstream	3,400	30 minutes			Size	20
	Upstream	3,410	2 hr 10 min over the	2.76		Mass	22
	Downstream	3,400	4 hr 20 min same 6 hr period	6.404		Mass	21
Denison, Texas	Upstream Hor.	4,560	60 minutes	4.18	10 cm-Isokinetic	Size & Mass	23
	Upstream Vert.	4,560	60 minutes	4.18		Size & Mass	23
	Downstream	---	16 minutes	4.30	20 cm x 25 cm Hi-Vol	Size	5
	Downstream	---	5 minutes	1.40		Size	7
	Downstream	---	30 minutes	8.49		Size	18
	Downstream	---	5 hr 7 min	195.00		Mass	11
Asbestos, Canada	Upstream	665	≈ 1 sec (1.7 ℓ)	1.7×10^{-3}	10 cm-Isokinetic	Size	27
	Upstream	665	≈ 1 sec (3.54 ℓ)	3.54×10^{-3}		Size	34
	Upstream	665	≈ 1 sec (1.4 ℓ)	1.4×10^{-3}		Size	25
	Upstream	665	≈ 1 sec (2.83 ℓ)	2.83×10^{-3}		Mass	28
	Downstream	---	10 minutes	0.57	10 cm--Hi-Vol	Size	42
	Downstream	---	30 minutes	1.70		Size	43
	Downstream	---	5 hours	101.8		Mass	41
Eden Mills, Vermont	Upstream	1,330	1 second	4.25×10^{-4}	10 cm-Isokinetic	Size	31
	Upstream	1,330	5 seconds			Size	32
	Upstream	1,330	30 seconds			Size	33
	Upstream	1,330	1 hr 10 min	3.08		Mass	26
	Downstream	---	10 minutes	4.10	10 cm--Hi Vol	Size	37
	Downstream	---	30 minutes	11.90		Size	38
	Downstream	---	1 hour	23.80		Size	36
	Downstream	---	6 hours	143.00		Mass	40

Table 18. SAMPLE WEIGHTS AND MASS EFFICIENCY DATA

Plant Location	Sampling Location	Volume Sampled m^3 (ft^3)	Filter Code Number (1)	Sample Weight on Filter, g	Sample Weight in Cyclone and Probe, g	Total Sample Weight, g	Dust Concentration g/m^3	Mass Removal Efficiency %
Waukegan, Illinois	Upstream	1.755 (62)	11	0.2270	7.3822	7.6092	4.336	100 with experimental limits
	Downstream	12.984 (458.8)	12	0.0000	0.0000	0.0000	0.000	
Marshville, North Carolina	Upstream	2.765 (97.7)	22	0.0383	1.5511	1.5894	0.580	>99.99
	Downstream	6.404 (226.3)	21	0.0002	0.0000	0.0002	0.000031	
Denison, Texas	Upstream	4.183 (147.8)	23	0.8895	53.0758	53.9653	12.901	100 with experimental limits
	Downstream	196.0 (6,907.5)	11 (A)	0.0000	---	0.0000	0.000	
Asbestos, Quebec	Upstream	1.40 (2) (0.05)	28	0.0003	0.1645	0.1648	117.0	>99.99
	Downstream	101.80 (3,600.)	41 (B)	0.0103	---	0.0103	0.0001	
Eden Mills, Vermont	Upstream	3.085 (109)	26	1.6733	16.2487	17.9220	5.804	>99.99
	Downstream	143 (5,040)	40 (B)	0.0084	---	0.0084	0.000059	

(1) All samples taken except: A) 25 x 20 cm Hi-Vol, B) 10 cm diameter Hi-Vol.

(2) Heavy dust loading prevented sampling for more than a few seconds.

Table 19. TOTAL FIBER COUNTS AND FIBER REMOVAL EFFICIENCIES

Plant Location	Sampling Location	Volume of Air Sampled (m^3)	Optical Microscope, 500X		Electron Microscope, 16,364X		Filter No.
			Total Fibers (No. of Fibers/m^3)	Efficiency (%)	Total Fibers (No. of Fibers/m^3)	Efficiency (%)	
Waukegan, Illinois	Upstream	1.75	$> 10^{10}$ (1)	----	$> 10^{14}$ (1)	----	11
	Downstream	13.0	6.37×10^3	> 99.99	1.08×10^7	> 99.99	12
Marshville, North Carolina	Upstream	2.83×10^{-3}	8.07×10^8	----	2.45×10^{11}	----	17
	Downstream	4.42×10^{-1}	1.42×10^4	> 99.99	3.28×10^9	98.69	20
	Downstream	5.94×10^{-2}	----	----	5.04×10^9	97.94	18
Denison, Texas	Upstream	4.18	1.02×10^6	----	3.20×10^7	----	23
	Downstream	8.49	2.88×10^4	97.18	1.38×10^7	57.90	18B
Asbestos, Quebec	Upstream	1.69×10^{-3}	2.19×10^9	----	1.24×10^{12}	----	27
	Downstream	1.70	8.33×10^5	99.96	1.44×10^9	99.88	43B
Eden Mills, Vermont	Upstream	4.25×10^{-4}	1.42×10^9	----	1.36×10^{13}	----	31
	Downstream	23.8	4.52×10^4	> 99.99	1.29×10^8	> 99.99	36B

(1) Samples too dense to count; sample diluted for size distribution.

$$\text{Efficiency (\%)} = 100\left(1 - \frac{\text{no. of fibers downstream}}{\text{no. of fibers upstream}}\right)$$

Table 20. OPTICAL MICROSCOPE (500X) SIZE DISTRIBUTIONS AND FRACTIONAL REMOVAL EFFICIENCIES

			Size Distributions (by length)												
			1.5-10 μm			10-20 μm			20-30 μm			> 30 μm			
Sampling Site	Sampling Location	Total Fibers (No. of Fibers per m^3)	Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	Filter No.
Waukegan, Illinois	Upstream	$> 10^{10}$**	$>5.06\times10^9$	50.6	----	$>2.10\times10^9$	21.0	----	$>1.67\times10^9$	16.7	----	$>1.17\times10^9$	11.7	----	11
	Downstream	6.37×10^3	2.70×10^3	42.4	>99.99	2.31×10^3	36.4	>99.99	5.80×10^2	9.1	>99.99	7.71×10^2	12.1	>99.99	12
Marshville, North Carolina	Upstream	8.07×10^8	5.46×10^8	67.6	----	1.78×10^8	22.0	----	4.84×10^7	6.0	----	3.55×10^7	4.4	----	17
	Downstream	1.42×10^4*	1.14×10^4	80.0	>99.99	2.84×10^3	20.0	>99.99	0.0	0.0	100	0.0	0.0	100	20
Denison, Texas	Upstream	1.02×10^6	7.32×10^5	71.8	----	1.92×10^5	18.8	----	8.57×10^4	7.4	----	1.53×10^4	1.5	----	23
	Downstream	2.88×10^4	2.19×10^4	76.2	97.01	5.99×10^3	20.8	96.88	5.76×10^2	2.0	99.33	2.88×10^2	1.0	98.12	18B
Asbestos, Quebec	Upstream	2.19×10^9	1.31×10^9	59.7	----	6.61×10^8	30.2	----	1.77×10^8	8.1	----	5.26×10^7	2.4	----	27
	Downstream	8.33×10^5	6.27×10^5	75.3	99.95	1.48×10^5	17.8	99.98	4.00×10^4	4.8	99.98	1.75×10^5	2.1	99.67	43B
Eden Mills, Vermont	Upstream	1.42×10^9	1.22×10^9	86.8	----	1.48×10^8	10.4	----	2.70×10^7	1.9	----	1.28×10^7	0.9	----	31
	Downstream	4.52×10^4	3.42×10^4	75.7	>99.99	8.14×10^3	18.0	>99.99	2.03×10^3	4.5	99.99	8.13×10^8	1.8	99.99	36B

* Sample contained five fibers in 100 fields.
** Sample too dense to count; sample diluted for size distribution.

$$\text{Efficiency (\%)} = 100\left(1 - \frac{\text{no. of fibers downstream}}{\text{no. of fibers upstream}}\right)$$

Table 21. ELECTRON MICROSCOPE (16,364X) SIZE DISTRIBUTION AND FRACTIONAL REMOVAL EFFICIENCIES

Sampling Site	Sampling Location	Total Fibers (No. of Fibers per m^3)	Size Distributions (by length)															Filter No.
			<0.06 μm			0.06-0.18 μm			0.18-0.36 μm			0.36-0.54 μm			0.54-1.50 μm			
			Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	Fiber Count (No. of Fibers per m^3)	% of Sample	Efficiency (%)	
Waukegan, Illinois	Upstream	$>10^{14}$(1)	$>8.7\times10^{12}$	8.7	----	$>1.06\times10^{13}$	10.6	----	$>1.25\times10^{13}$	12.5	----	$>1.83\times10^{13}$	18.3	----	$>5.0\times10^{13}$	50.0	----	11
	Downstream	1.08×10^{7}	0.0	0.0	100	0.0	0.0	0.0	1.88×10^{6}	17.4	>99.99	1.40×10^{6}	13.0	>99.99	7.52×10^{6}	69.6	>99.99	12
Marshville, North Carolina	Upstream	2.45×10^{11}	2.74×10^{10}	11.2	----	1.10×10^{11}	44.9	----	6.05×10^{10}	24.7	----	1.37×10^{10}	5.6	----	3.31×10^{10}	13.5	----	17
	Downstream	5.04×10^{9}	1.28×10^{9}	25.3	95.33	2.89×10^{9}	57.3	97.37	6.90×10^{8}	13.7	99.89	1.06×10^{8}	2.1	99.23	8.57×10^{7}	1.7	99.74	20
	Downstream	3.28×10^{9}	5.25×10^{8}	16.0	98.08	1.88×10^{9}	57.3	98.29	6.56×10^{8}	20.0	98.92	8.86×10^{7}	2.7	99.35	1.31×10^{8}	4.0	99.60	18
Denison, Texas	Upstream	3.20×10^{7}	0.0	0.0	----	0.0	0.0	----	4.35×10^{6}	13.6	----	4.35×10^{6}	13.6	----	2.33×10^{7}	72.7	----	23
	Downstream	1.38×10^{7}	0.0	0.0	----	1.10×10^{6}	8.0	(2)	1.66×10^{6}	12.0	61.80	3.86×10^{6}	28.0	11.30	7.18×10^{6}	52.0	69.20	18B
Asbestos, Quebec	Upstream	1.24×10^{12}	0.0	0.0	----	2.36×10^{10}	1.9	----	6.94×10^{10}	5.6	----	1.39×10^{11}	11.2	----	1.01×10^{13}	81.3	----	27
	Downstream	1.44×10^{9}	3.48×10^{8}	24.2	(2)	7.53×10^{8}	52.3	96.81	1.38×10^{8}	9.6	99.80	1.73×10^{7}	1.2	99.99	1.83×10^{8}	12.7	>99.99	43B
Eden Mills, Vermont	Upstream	1.36×10^{13}	2.12×10^{12}	15.6	----	6.17×10^{12}	45.4	----	2.64×10^{12}	19.4	----	1.32×10^{12}	9.7	----	1.35×10^{12}	9.9	----	31
	Downstream	1.29×10^{8}	1.24×10^{7}	9.6	>99.99	4.26×10^{7}	33.0	>99.99	1.86×10^{7}	14.4	>99.99	1.48×10^{7}	11.5	>99.99	4.14×10^{7}	32.1	>99.99	36B

(1) Samples too dense to count; total fiber count $> 10^{14}$ fibers/m^3.
(2) Negative efficiency indicated within experimental limits.

$$\text{Efficiency (\%)} = 100\left[1 - \frac{\text{no. of fibers downstream}}{\text{no. of fibers upstream}}\right]$$

efficiency is of importance. No other comparable data was found in the literature. In general terms, it can be seen from Table 19 that the number of fibers emitted which were greater than 1.5 μm in length was of the order of 10^4 fibers per cubic meter at the five locations. At the same time, the number of fibers emitted which were in the very small size group of 0.06 to 1.5 μm in length was of the order of 10^8 fibers per cubic meter.

Two reasons could be given to explain the above result. Either the collection efficiency for the very small particles could be very low or there could be very many more fibers challenging the fabric filter at the same collection efficiency. From Table 19, it is seen that, in general terms, the collection efficiency for fibers greater than 1.5 μm was in excess of 99.99%, while the collection efficiency for the fibers less than 1.5 μm in length was greater than 98%. (The one low result, 57.9%, for the collection efficiency at the Denison plant, could be in error, although it is noted that it also had the lowest efficiency in the greater than 1.5 μm size group at 97.18%.) Obviously then, the reason for the very large number of fibers emitted in the 0.6 to 1.5 μm size range is the enormously large numbers of fibers present in this range and not from any significant change in the collection efficiency with particle size.

The form of the fractional efficiency curves for fabric filters have been studied by a number of workers[24,25]. Peterson and Whitby[26] reported that the fractional efficiency goes to a minimum at a particle size of about 0.3 μm, and increases in efficiency for particle sizes above and below this point. Their conclusions were based on the fractional efficiency measurements made using a monodisperse aerosol to challenge the filter. Colley[27] has found that while the efficiency is at a minimum with a particle size of 0.1-0.2 μm, there is no evidence to show that the efficiency actually increases with decreasing particle size beyond this size. The explanation for the observed flattening of the curve is that larger particles have a comparatively high inertia and the path of the particles is not altered by Brownian movement. As the particles decrease in size, Brownian movement becomes more effective and will cause the particles to alter their path such that they are captured by the fabric.

The present results show a pronounced flattening of the fractional efficiency curve, indicating that the smaller particles, which might be expected to penetrate the filter, are being captured by Brownian movement. For asbestos, which has a fibrous form, there will be a more complicated aerodynamic approach theory than for simple spheres. The fibrous form could aid capture efficiency if the particles approach the fabric length-ways on. Alternatively, the capture efficiency could be reduced if the fibers line up in the direction of flow and present a small cross-section for capture.

A highly significant point resulting from this study is the fact that, in very many instances, air is recirculated within an asbestos plant. Plant operators have considered this to be reasonable if the return air can be shown to contain asbestos at a level lower than the OSHA standard of less than 2 fibers per cubic centimeter, where a fiber is only counted if it is greater than 5 cm in length. It has been shown here that while the number of fibers greater than 5 μm is low, there are very large numbers of fibers less than 5 μm. However, plant operators who recirculate plant air are inadvertently exposing their workers to very high levels of very small fibers whose health significance has not been established.

SECTION 7

ESTIMATE OF ASBESTOS DISPERSION

INTRODUCTION

Two methods were used to estimate the dispersion of the asbestos emissions from the source. Both were based on the well-known equations of Pasquill[28] as restated by Gifford[29] . The first method involved the manual calculation of the dispersion using the Binormal Continuous Plume Dispersion Model as detailed by Turner[30] . This technique enables predictions of the ambient pollutant concentration downwind from a known source under given metoerological conditions.

The second method utilized the Climatological Dispersion Model (CDM). This model predicts the long-term (seasonal or annual) quasi-stable pollutant concentrations in an area surrounding the source. The long-term wind rose data, obtainable from the National Climactic Center, is required for this model, and, because of the very large number of computations, it is only suitable for use by computer. Results using the CDM were found to be inconsistent due to the inherent limitations of the model. For this reason, only those results obtained with the first model are included with this report.

THE BINORMAL CONTINUOUS PLUME DISPERSION MODEL

The system considered in this model is shown in Figure 2. The x-axis extends horizontally in the direction of the mean wind. The y-axis is in the horizontal plane perpendicular to the x-axis, and the z-axis extends vertically. The plume travels along a parallel to the x-axis from point H, which represents the sum of the physical stack height, h, and the plume rise, ΔH.

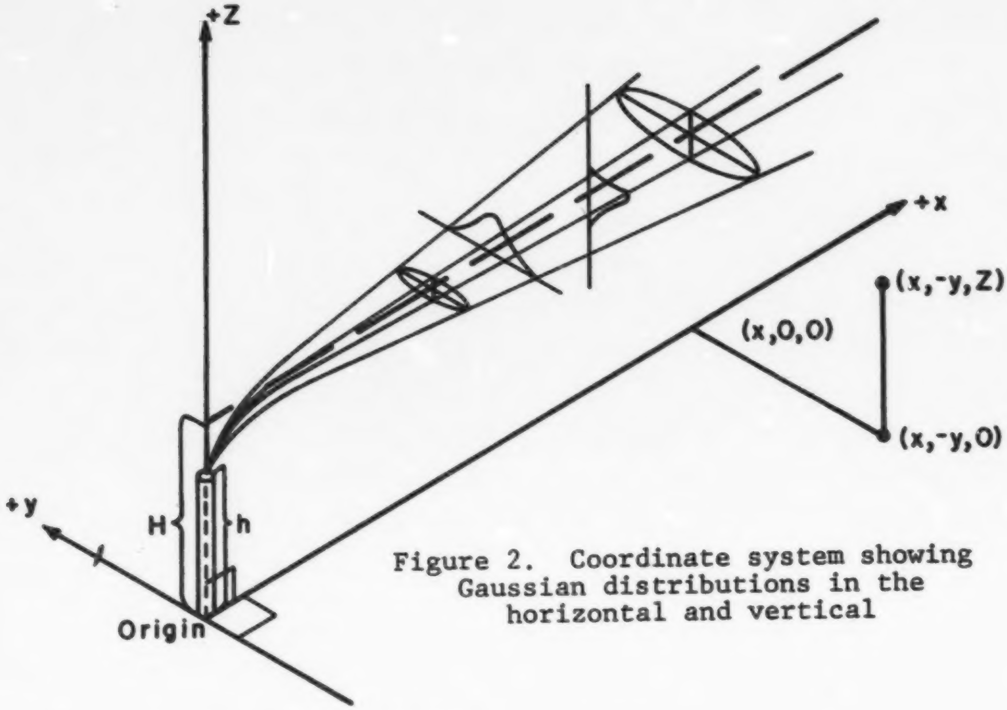

Figure 2. Coordinate system showing Gaussian distributions in the horizontal and vertical

The concentration, X, of the aerosolized particles (i.e., less than about 20 μm diameter) at x,y,z from a continuous source with an effective emission height, H, is given by equation (1).

$$X(x,y,z;H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{\exp\left[-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)\right]\right\} \quad (1)$$

Any consistent set of units may be used, for the present study:

X = concentration (fibers/m^3)

Q = emission rate (fibers/sec)

u = mean wind speed (m/sec)

H,x,y,z = effective stack height and coordinate (m)

σ_y,σ_z = standard deviations of plume coordinate (m)

In establishing this equation, a number of assumptions are made:

- The plume spread has a Gaussian distribution in both the horizontal and vertical planes.
- The wind is constant in speed and direction.
- The emission rate is uniform.
- Total reflection of the plume takes place at the earth's surface, i.e., there is no deposition or reaction at the surface.
- There is no diffusion in the direction of the plume travel.

For concentrations calculated at ground level, i.e., $z = 0$, and downwind along the centerline of the plume, i.e., $y = 0$, the equation simplifies to

$$X(x,0,0;H) = \frac{Q}{\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \tag{2}$$

In most real circunstances, a stable layer exists above the unstable lower layer with the effect of restricting the vertical diffusion. The model can be modified to account for this situation by considering the height of the base of the stable layer from the ground level to be L. At a height $2.15\sigma_z$ above the plume centerline, the concentration is one tenth of the concentration at the centerline at the same distance along x. When one tenth of the plume centerline concentration reaches the stable layer, height L, it is assumed that the distribution is affected by the stable layer. At this point, which is called x_L, $2.15\sigma_z = L$, or $\sigma_z = 0.47L$.

At distance, x_L, the plume is assumed to have a Gaussian distribution in the vertical. It is further assumed that when the plume travels twice this distance, to $2x_L$, the plume has become uniformly distributed between the earth's surface and the stable layer at height L. Between these limits, the concentration does not change with height. At distances greater than $2x_L$, the downwind centerline concentration is calculated from:

$$X(x,0,z;H) = \frac{Q}{\sqrt{2\pi}\sigma_y Lu} \qquad (3)$$

for any value of z from 0 to L.

THE METHOD OF CALCULATION USING THE BINORMAL CONTINUOUS PLUME DISPERSION MODEL

As input for the model, the following basic information is required.

- The mean wind speed, u, (m/sec)
- The source emission rate, Q (fibers/sec)
- The effective source height, H (m)
- Stable layer height, L, for daytime and nighttime conditions (m)
- The stability class

The values of mean wind speed, u, source emission rate, Q, and the effective source height, H, are measured values taken at a given site. The stable layer height, L, for daytime and nighttime conditions were assumed from the average conditions reported in the literature. Values of 800 m and 150 m were assumed for daytime and nighttime conditions, respectively. The stability class was taken from observations of the meteorological conditions and reference to Table 22.

Table 22. KEY TO STABILITY CATEGORIES

Surface Wind Speed at 10 m (m/sec)	Day			Night	
	Incoming Solar Radiation			Thinly Overcast or > 4/8 Low Cloud	>3/8 Cloud
	Strong	Moderate	Slight		
< 2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

Note: The neutral class D should be assumed for overcast conditions during day or night.

Ambient air concentrations downwind from the source were calculated using equation (2) for distances of x less than x_L and from equation (3) for distances of x greater than $2x_L$. The distance x_L is found from the assumed stable layer height, L, which gives the value of σ_z (from $\sigma_z = 0.47L$). The distance x_L can then be found directly from Figure 3.3 in the Atmospheric Dispersion Estimates Workbook[30].

The only remaining unknown is then σ_y, which can be found for a given distance from the source directly from Figure 3.2 in Reference 30.

RESULTS FROM THE BINORMAL CONTINUOUS PLUME DISPERSION MODEL

Using the service terms for each site as shown in Table 23, values for the downwind concentration of asbestos fibers were estimated for both daytime and nighttime conditions using two stability classes in each instance. Detailed results for distances up to 30 kilometers are tabulated in Appendix B. In these tables, separate values have been computed for those fibers observed by optical microscope (i.e., greater than 1.5 μm) and those observed by electron microscope (i.e., less than 1.5 μm).

The results for the five locations at Waukegan, Illinois, Denison, Texas, Marshville, North Carolina, Asbestos, Canada, and Eden Mills, Vermont, are displayed graphically in Figures 3, 4, 5, 6, and 7. The fiber concentration, x, plotted on the graphs, represents the number of fibers observed by electron microscope, although this may be taken as the total number of fibers with very little error, since, in general, the number of fibers observed under the electron microscope exceeded those observed under the optical microscope by about three orders of magnitude.

Fiber concentrations are observed to increase initially with distance from the source due to the effect of plume height. However, after a short distance of about 0.1 to 0.3 kilometers, there is a rapid fall in concentration until about 10 kilometers distance after which the graph asymptotically approaches ambient air fiber concentration.

The effect of the stable layer height is pronounced; much higher values are estimated to occur during nighttime due to the lowering of the height of the stable layer. Typically, this difference is about an order of magnitude in the distance range of 10 to 30 kilometers from the source.

Table 23. DISPERSION EQUATION SOURCE TERMS

Plant Location	Baghouse Air Throughput m^3/min	Emitted Fiber Concentration		Source Term	
		From Optical Microscope Analysis Number/m^3	From Electron Microscope Analysis Number/m^3	From Optical Microscope Analysis Fibers/sec	From Electron Microscope Analysis Fibers/sec
Waukegan, Ill.	1.13×10^3	6.4×10^3	1.1×10^7	1.2×10^5	2.0×10^8
Marshville, N.C.	4.73×10^2	1.4×10^4	5.0×10^9	1.1×10^5	4.0×10^{10}
Denison, Tex.	7.36×10^2	2.9×10^4	1.4×10^7	3.5×10^5	1.7×10^8
Asbestos, Que.	1.27×10^5	8.3×10^5	1.4×10^9	7.6×10^8	3.1×10^{12}
Eden Mills, Vt.	8.49×10^3	4.5×10^4	1.3×10^8	6.4×10^6	1.8×10^{10}

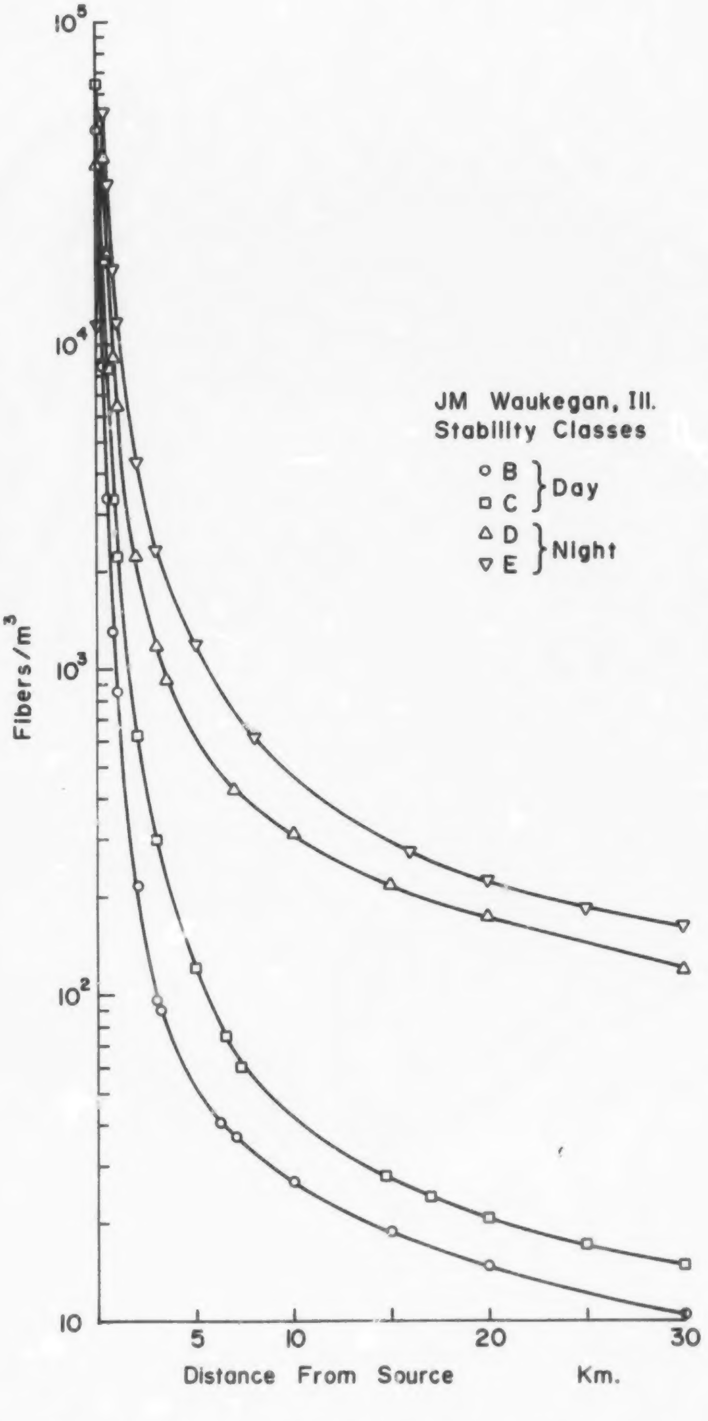

Figure 3. The concentration of asbestos fibers with distance from source at four stability conditions for Johns-Manville, Waukegan, Illinois

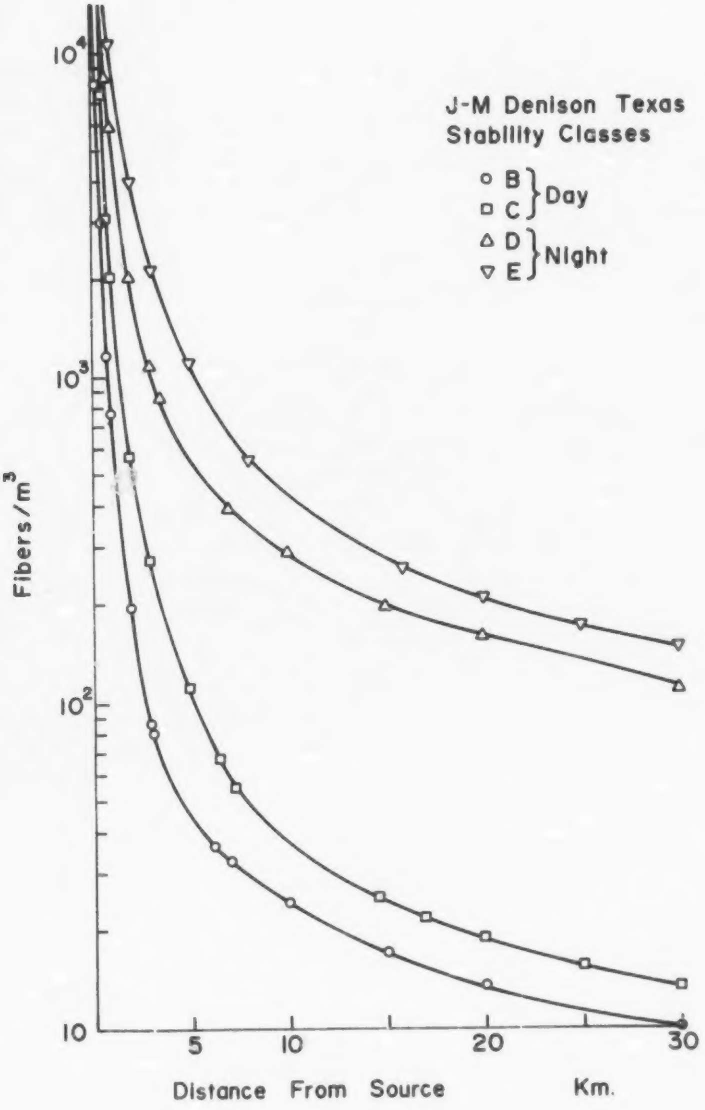

Figure 4. The concentration of asbestos fibers with distance from source at four stability conditions for Johns-Manville, Denison, Texas

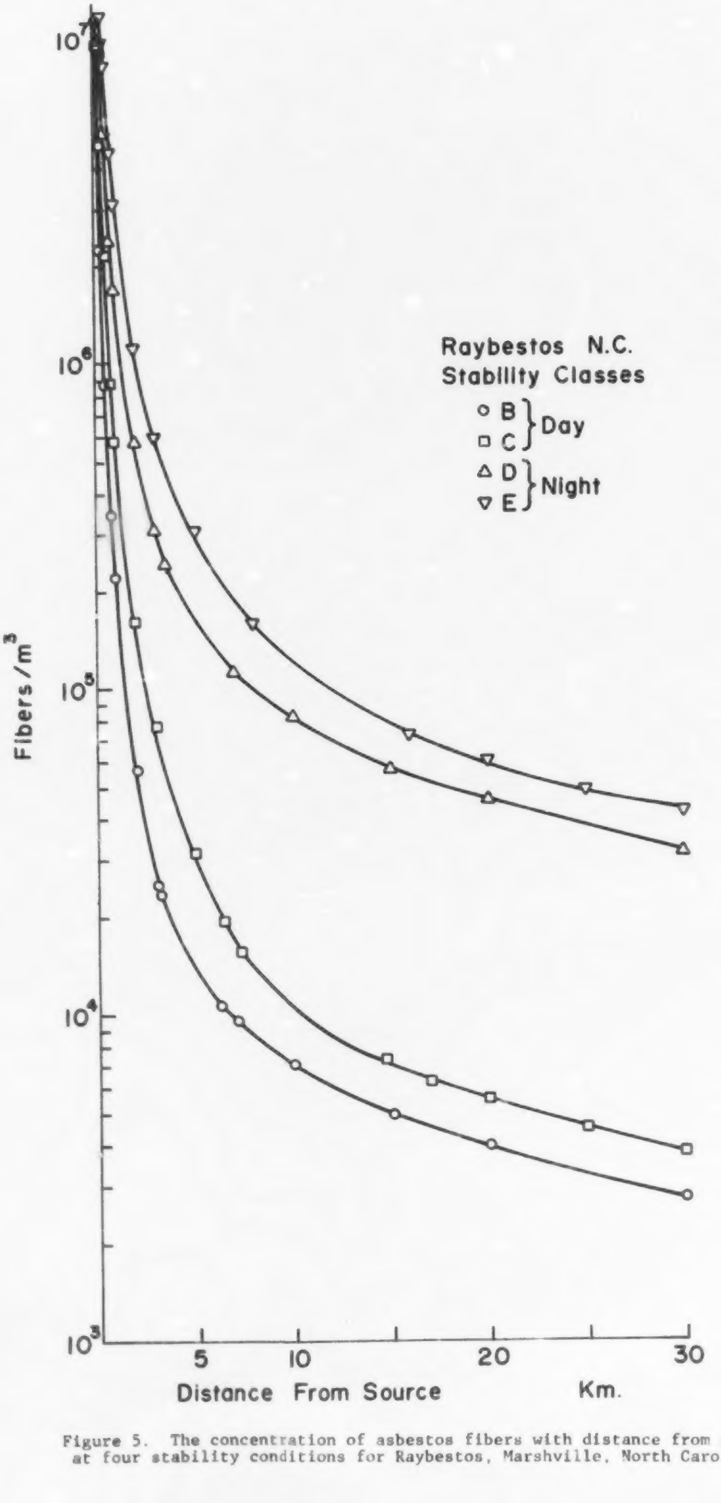

Figure 5. The concentration of asbestos fibers with distance from source at four stability conditions for Raybestos, Marshville, North Carolina

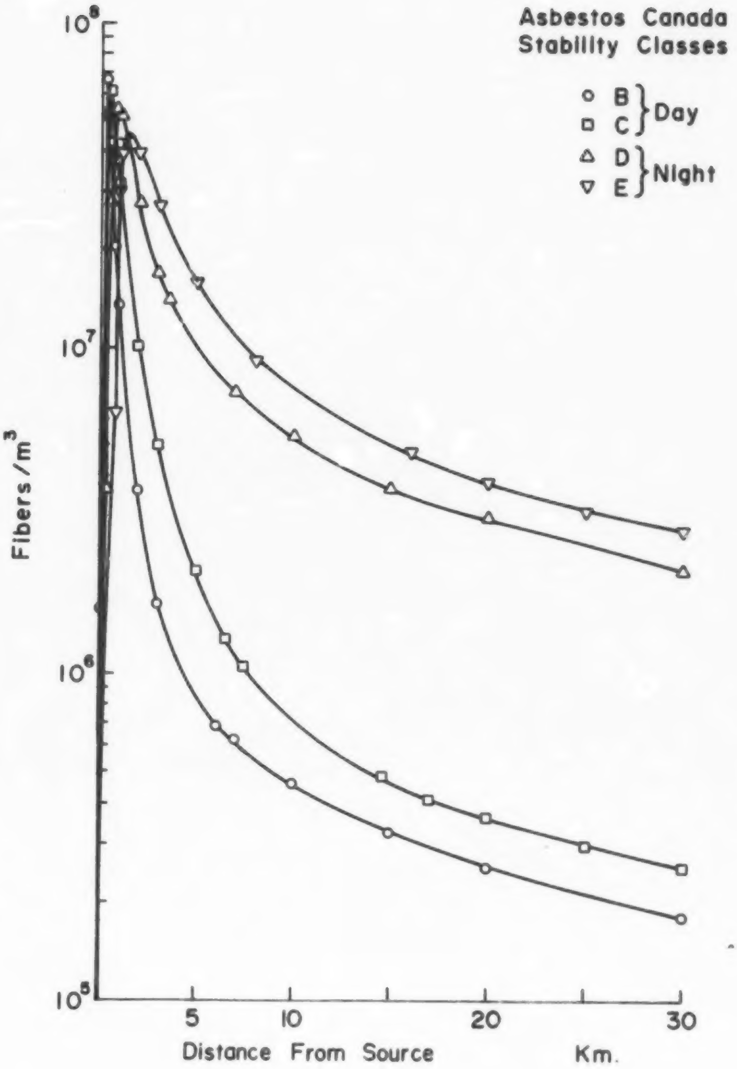

Figure 6. The concentration of asbestos fibers with distance from source at four stability conditions for Johns-Manville, Asbestos, Canada

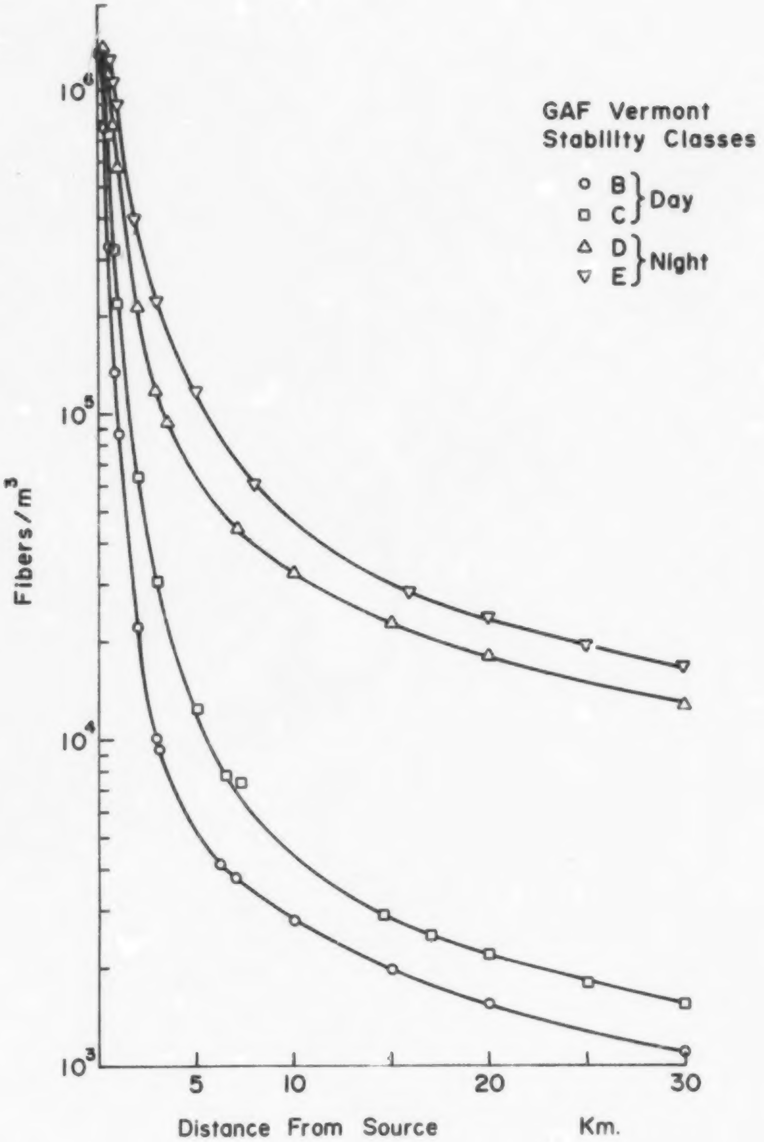

Figure 7. The concentration of asbestos fibers with distance from source at four stability conditions for GAF, Eden Mills, Vermont

SECTION 8

REFERENCES

1 Roper, G. W. Asbestos Mill Filters. IIT Research Institute. (Presented at IIT Research Institute Seminar on Asbestos, Chicago, Illinois. 1972).

2. Goldfield, Joseph. Fabric Filters in Asbestos Mining and Manufacturing. (Presented at APCO Fabric Filter Symposium. Charleston, Virginia. 1971).

3. Hills, D. W. Economics of Dust Control. Annals of the New York Academy of Science. 132:322-334, 1964.

4. Rozovsky, H. Air in Asbestos Milling. Canadian Mining Journal. 78:95-103, May 1957.

5. Wieschhaus, L. J. Recovering Asbestos Floats with Dust Collectors. Rock Products. 50(8):104-105, 1947.

6. Dust Control Methods. Coal Age. 72(8):56-62, 1967.

7. Dust Collection Plants. Cement Technology. Pp. 229-232, November/December 1972.

8. Quebec Asbestos Producers Join Forces in Fighting Dust. Engineering and Mining Journal. 174(10):82-83, 1973.

9. Control Techniques for Asbestos Emissions. Johns-Manville Research and Development Division internal report.

10. Precipitators and Filters at 'Cleanest Ever' Cement Works. Filtration and Separation. 10(1):40, 1973.

11. Cross, F. L. Baghouse Filtration of Air Pollutants. Pollution Engineering. 6(2):25-34, 1974.

12. Dick, G. A. Fabric Filters. Canadian Mining Journal. 91(10):72-80, 1972.

13. Jensen, Kenneth E. Concepts of Fabric Filtration for Air Pollution Control. Filtration and Separation. 6(3):254,257, 1969.

14. Pring, R. T. Reducing Baghouse Maintenance by Design. Minerals Processing. 11(5):8-13, 1970.

15. Jones, A. H. How to Improve Maintenance of Fabric Dust Collectors. Minerals Processing. 10(5):21-23,35, 1969.

16. Dust and Fume Control Equipment in the Non-Ferrous Metals Industry. Filtration and Separation. 10(1):48, 1973.

17. Design and Operation of Asphalt Plant Bag Collectors. Pit and Quarry. 65(11):109, 1973.

18. Reigel, S. A., R. P. Bundy, and C. D. Doyle. Baghouses -- What to Know Before You Buy. Pollution Engineering. 5(5):32-34, 1973.

19. Cosby, W. T. and G. Punch. Dust Filters and Collectors, Cost and Performance of Filtration and Separation Equipment. Filtration and Separation. 5(3):252-255,270, 1968.

20. Selikoff, I. J., E. C. Hammond, and E. Heimann. Critical Evaluation of Disease Hazards Associated with Community Asbestos Air Pollution. Proceedings of the Second International Clean Air Congress. Pp. 165-171, 1970.

21. Minifie, F. G. and A. J. Moyes. Low Cost Electrostatic Precipitator. Filtration and Separation. 9(1):52-59, 1972.

22. Control Techniques for Asbestos Air Pollution. United States Environmental Protection Agency Report No. AP-117, 1973.

23. Hailstone, R. E. Air Pollution in the Cement Industries. Minerals Processing. 10(5):11-15, 1969.

24. Stairmand, C. J. The Design and Performance of Modern Gas-Cleaning Equipment. Jnl. Inst. of Fuel. Pp. 58-81, February 1956.

25. Sommerlad, R. S. Fabric Filtration -- State of the Art. Livingston, New Jersey, Foster Wheeler Corporation, March 6, 1967.

26. Petersen, C. M. and K. T. Whitby. Fractional Efficiency Characteristics of Unit Type Collectors. ASHRAE Journal. May 1965.

27. Colley, D. G. Stack Sampling Yields Fractional Efficiencies for Dust Collectors. (Presented at Air Pollution Control Conference. Purdue University. October, 1970.)

28. Pasquill, F. The Estimation of the Dispersion of Windborne Material. Meteorol. Mag. 90(1063):33-49, 1961.

29. Gifford, F. A. Uses of Routine Meteorological Observations for Estimating Atmospheric Dispersion. Nuclear Safety. 2(4):47-51, 1961.

30. Turner, D. B. Workbook of Atmospheric Dispersion Estimates. PHS Publication No. 999-AP-26, 1970.

SECTION 9

APPENDICES

Page

A. Selected Bibliography and Abstracts 83

B. Binormal Continuous Plume Dispersion Model Results 110

Appendix A

SELECTED BIBLIOGRAPHY AND ABSTRACTS

SELECTED BIBLIOGRAPHY AND ABSTRACTS

Addingley, C.G., "Dust Measurement and Monitoring in the Asbestos Industry," Annals of the New York Academy of Science, 132, pp 298-305, 1965.

All methods of dust counting of asbestos air concentrations require examination under a microscope. The Royco Particle Counter, using light scattering principles, is investigated as an on-line monitor for asbestos concentrations in the air. Results show agreement with membrane filter techniques to within 25%.

Addingley, C.G., "Asbestos Dust and Its Measurements," Annals of Occupational Hygiene, 9, pp 73-82, 1966.

The nature of asbestos dust and the testing requirements are discussed. Existing standard methods are briefly reviewed.

The development of a membrane filter method of dust counting for asbestos is described in detail. It is thought to be an improvement on existing methods.

Tyndallometric methods are considered, and a description of the application of the "Royco" Particle Counter, an instrument based on this principle, to factory testing is described. It is believed that this instrument represents a big advance in routine test methods.

Aldred, Robert, "Dust Filtration Apparatus," British Patent No. 1293592, 1969.

The patent discusses dust filtration in mines, avoiding the use of water, which gives further problems in cooling the mine, etc. Two stages are used, the first being a sort of cyclone, with deflectors, and then a band filter for retaining the finer dust. A fan is used downstream of the filter unit to pull the dirty air stream through the unit.

Anonymous, "Bag Collects 60,000 Tons of Sinter Dust," Air Engineering, 10, No. 7, pp 8, 11, 1968.

The dust collection system on the sinter line of the Bethlehem, Pennsylvania plant of the Bethlehem Steel Corporation is described. The system operates at 99% efficiency and has reclaimed over 60,000 tons of dusts over five years.

Anonymous, "Bag Life Extended at Copper Refinery," Air Engineering, 11, No. 1, pp 18-19, 1969.

The baghouse at the Carteret, New Jersey plant of AMAX's United States Metals Refining Company is described. Adoption of a new filter fabric made of Dupont's high temperature fiber, "Nomex" nylon, has resulted in an effective bag life 14 times greater than that of glass fiber bags.

Anonymous, "Control Techniques for Asbestos Air Pollution," United States Environmental Protection Agency report No. AP-117, 1973.

Asbestos is the generic name for a group of hydrated mineral silicates that occur naturally in a fibrous form. The technological utility of asbestos derives from its physical strength, resistance to thermal degradation, resistance to chemical attack, and ability to be subdivided into fine fibers.

The subdivision of asbestos into fine fibers produces particulate matter that is readily dispersed into the atmosphere. Adverse effects of airborne asbestos on human health have been associated primarily with direct and indirect occupational exposures, but a level of asbestos exposure below which there is no detectable risk of adverse health effects to the general population has not yet been identified. Because of the lack of a practical technique of adequate sensitivity for measuring small concentrations of airborne asbestos, neither accurate emission factors nor emission-effect relationships are available.

Engineering appraisals, based on limited data, indicate that the milling and basic processing of asbestos ore (crushing and screening the ore and aspirating the fiber to cyclones for grading) and the manufacture of asbestos-containing friction materials, asbestos-cement products, vinyl-asbestos tile, asbestos textiles, and asbestos paper account for over 85 percent of total asbestos emissions. Other sources include: (1) the manufacture of other products containing asbestos, such as paints, coatings, adhesives, plastics, rubber materials, and molded insulating materials; (2) the use of spray on asbestos products, such as those used for fireproofing or insulating; (3) the demolition of buildings or structures containing asbestos fireproofing or insulating materials; and (4) the sawing, grinding, or machining of materials that contain asbestos, such as brake linings and molded pipe insulation. In most of the manufacturing operations, the major emissions of asbestos occur when the dry asbestos is being handled, mixed with other dry materials, or dumped into the wet product mix, but the weaving of asbestos fibers into textiles and the machining or sanding of hard asbestos products also produce major emissions.

Emissions are controlled in several ways: (1) by careful handling of dry materials to avoid generating dust; (2) by enclosing dusty operations; (3) by substituting wet processes for dry processes; (4) by wetting dry materials before handling, sawing, or grinding; (5) by cleaning the dust-laden air by drawing it into ducts that lead to fabric filters; and (6) by reducing the amount of asbestos added to products the use of which leads to the generation of emissions. The last technique is particularly applicable to situations where the control of emissions by other methods is very difficult, as with spray application of insulation or demolition of structures. The costs of needed emission control techniques can be estimated from those associated with existing practices.

Anonymous, "Control Techniques for Asbestos Emissions," Johns-Manville Corporation Research and Engineering Division internal report, 1970.

Johns-Manville is the largest producer of asbestos fiber and asbestos products in the free world. During the past 14 years, Johns-Manville has installed over 100 air and dust handling systems in its plants. The costs of these systems exceeded $18,000,000. The largest single installation was at the Jeffrey Mill No. 5 in Asbestos, Quebec. This baghouse handles 1.27×10^8 lpm (4×10^6 cfm) and the total cost was $8,000,000.

Anonymous, "Design and Operation of Asphalt Plant Bag Collectors," Pit and Quarry, 65, No. 11, p 109, 1973.

Dust-laden exhaust gases from dryers in asphalt processing plants are cleaned using baghouses. Operation and design of baghouse dust collection systems is described.

Anonymous, "Dust and Fume Control Equipment in the Non-Ferrous Metals Industry," Filtration and Separation, 10, No. 1, p. 48, 1973.

Bag filters, electrostatic precipitators and wet scrubbers are the equipment most used by the British non-ferrous metals industry to cope with fume, grit and dust arising from smelting and other operations.

Emissions from the non-ferrous metals industry comprise dust and fine metallic particles, smoke from burning oil contaminating the raw materials, metallic oxide fumes, and, in the aluminum industry, chlorides and fluorides. Dust and metal particles are readily collected in settling chambers, cyclones, etc., but micron and submicron material (the worst problem) can only be collected by high efficiency bag filters, high pressure drop scrubbers or electrostatic precipitators.

Anonymous, "Dust Collection Plants," Cement Technology, November-December, pp 229-232, 1972.

The task imposed on dust collection plants as used in industry are many and various, resulting in the development of a range of dust collection plants based on a variety of working principles and designed to complement each other efficiently.

On the basis of details supplied by the customer regarding his specific problem, the most suitable dust collecting system for his particular system can be worked out, which may, in fact, consist of a combination of two different dust collection methods.

The types of equipment employed for dust collection come under the following general groups: (1) electrical dust precipitation; (2) cyclone dust collection; and (3) wet type dust collection.

Anonymous, "Dust Control Methods," Coal Age, 72, No. 8, pp 56-62, 1967.

The first step towards effective dust control is choosing equipment best suited to handle your dust problem. To do this requires an adequate understanding of dust control methods and dust collector characteristics.

The different types of dust collectors are categorized in terms of their characteristics, including size, efficiency, and their applications.

Anonymous, "Precipitators and Filters at 'Cleanest Ever' Cement Works," Filtration and Separation, 10, No. 1, p 40, 1973.

The dust collection system at the new four million tons per acre cement factory at Northfleet, Kent is described. Fabric filters are preferred for smaller gas flows where temperatures and humidity are not excessive, e.g. at conveyor transfer points, cement packing and loading plants, and in some cases cement mill exhausts. But for treating very large gas volumes and flow rates electrostatic precipitators are used, particularly where high humidities and temperatures are encountered, as, for example, in the main kiln exhaust, the exhaust of excess air from moving grate clinker coolers, and, in some cases, the ventilating air from large cement mills.

Anonymous, "Quebec Asbestos Producers Join Forces in Fighting Dust," Engineering and Mining Journal, 174, No. 10, pp 82-83, 1973.

The eastern townships of Quebec have been the center of the asbestos mining industry for nearly a century. In this area, approximately 115 miles east of Montreal, six mines produce approximately 29% of the world's asbestos. Because of close proximity of the towns to mine and mill operations, Quebec asbestos mining firms have long recognized the need to control the environment and have combined resources to do so. An Environmental Control Committee of the Quebec Asbestos Mining Association (QAMA) unites the competing companies in commitment of management, engineering, and environmental inspections to protect workers and communities. Substantial reduction of dust emission points throughout the asbestos plants has been achieved, often as a result of sharing hard-won knowledge among the member companies.

Aureille, R. and Blanchot, "Experimental Investigation on the Effect of Different Parameters on the Separation Efficiency of an Electrostatic Precipitator," Staub-Reinhalt Luft, 31, No. 9, pp 23-28, 1971.

To improve the efficiency of electrostatic precipitators for waste-gas cleaning of thermal power stations working with coal dust, Electricite de France, in its research and development center in Chatou, has erected a semi-industrial experimental electrostatic precipitator installation. With this installation, which is designed for horizontal flow of the waste gases, it is possible, during operation, not only to check the most important parameters likely to affect precipitator efficiency, but also to vary each individual parameter, while all other magnitudes remain unchanged. The experimental investigations extended from 1961 through 1969. Part of the results obtained are reported.

Berlyand, M.E., "Investigations of Atmospheric Diffusion Providing a Meteorological Basis for Air Pollution Control," Atmospheric Environment, 6, No. 6, pp 379-388, 1972.

A summary of the principal lines of inquiry into the problem of atmospheric diffusion, including practical applications, in the U.S.S.R. Topics summarized are Gaussian and K-theory diffusion models, plume and point-source diffusion methods, mulitple sources, and abnormal meteorological conditions.

Billings, Charles E., and Wilder, John, "Handbook of Fabric Filter Technology," GCA Corporation internal report No. GCA-TR-70-17-G, 1970.

This report is the state-of-the-art of fabric filters. Major topics discussed are: (1) operating principles; (2) areas of application; (3) technology of fabric filtration processes; (4) types of fabric filters commercially available; (5) fabric selection; (6) engineering design of fabric filtration systems; (7) performance of fabric filters; (8) economics; and (9) operation and maintenance of fabric filters.

British Occupational Hygiene Society Committee on Hygiene Standards, "Hygiene Standards for Airborne Amosite Asbestos Dust," Annals of Occupational Hygiene, 16, pp 1-5, 1973.

The sub-committee on asbestos has reviewed the information on the results of human exposure to airborne amosite dust and animal experiments. The sub-committee believes it has insufficient knowledge of the relationship between airborne amosite dust exposure and the risk of asbestos to permit an accurate statement of the degree of protection afforded by a specified hygiene standard. Nevertheless, on the basis of comparisons between the effects of amosite and chrysotile dust on men and animals it is recommended that the standards for amosite should be no less stringent than those for chrysotile.

The sub-committee believes that a proper and reasonable objective would be to reduce the risk of contracting asbestosis to 1 percent of those who have a lifetime's exposure to the dust. By 'asbestosis' this sub-committee means the earliest demonstrable effects on the lung due to asbestos. "The Hygiene Standards for Chrysotile Asbestos Dust" (British Occupational Hygiene Society, 1968) showed that the risk of being affected to the extent of having such early clinical signs will be less than 1 percent for an accumulated exposure of 100 fiber-year/cm^3. That is, for example, a concentration of 2 fiber/cm^3 for 50 years, 4 fiber/cm^3 for 25 years, or 10 fiber/cm^3 for 10 years. An accumulated exposure of 100 fiber-years per cm^3 is therefore recommended for amosite. It is further recommended that exposures to amosite asbestos which lie in certain ranges of dustiness be designated by categories according to the scheme recommended in the hygiene standards for chrysotile asbestos dust.

Busse, Adrian D.; Zimmerman, John R., "User's Guide for the Climatological Dispersion Model," U. S. Environmental Protection Agency report No. EPA-R4-73-024, 1973.

The Climatological Dispersion Model (CDM) determines long-term (seasonal or annual) quasi-stable pollutant concentrations at any ground-level receptor using average emission rates from point and area sources and a joint frequency distribution of wind direction, wind speed, and stability for the same period.

This model differs from the Air Quality Display Model (AQDM) primarily in the way in which concentrations are determined from area sources and in the use in the CDM of Briggs' plume rise formula and an assumed power law increase in wind speed with height that depends on stability.

The material presented is directed toward the engineer familiar with computer techniques and will enable him to perform calculations with the CDM. Technical details of the computer programming are discussed; complete descriptions of input, output, and a test case are given. Flow diagrams and a source program listing are included. Companion papers by Calder (1971) on the technical details of the model and by Turner et al. (1972) on validation are included.

Cheng, Lung, "Collection of Airborne Dust by Water Sprays," Industrial Engineering Chemical Process Design and Development, 12, No. 3, pp 221-225, 1973.

A general theoretical equation was developed for the collection efficiency of airborne dust particles by spray drops. The model assumes an inertial impaction collection mechanism and is based upon mean interdrop length and mean interparticle area. Particular attention was given to the optimum drop size for collection with open and also confined sprays from a high-pressure nozzle. This general model was specifically adapted to the collection of dust particles in a horizontal tunnel by a solid-cone water spray by including the effects of duct size and spray configuration. The theoretical collection efficiencies agreed reasonably well with experimental data. The present results can be used to select a specific spray nozzle that will provide optimum collection efficiency for airborne dust based upon the available water flow rate and the line pressure.

Cosby, W.T.; Punch, G., "Dust Filters and Collectors - Cost and Performance of Filtration and Separation Equipment," Filtration and Separation, 5, No. 3, pp 252-255, 270, 1968.

In arriving at the 'best buy' in gas cleaning plant, it is essential to consider the duties to be performed, methods of containing the dust or fume and its disposal after removal. In this paper, the authors try to show how the selection of equipment is influenced by factors other than the characteristics of particles and collectors. They base their cost comparison data on two hypothetical duties each demanding efficiencies of 98-99%. Annual costs are calculated for fabric filter, dry plate precipitators, and venturi scrubbers. The effect on collector costs of high initial gas temperatures are considered and the provision of cooling equipment is taken into account.

Cross, Frank L., Jr., "Baghouse Filtration of Air Pollutants," Pollution Engineering, 6, No. 2, pp 25-34, 1974.

Filtration is one of the oldest methods of source control and is especially desirable for the removal of particulate matter from a gas stream. Satisfactory efficiencies are obtained with this type of unit with only moderate power consumption and relatively low maintenance problems if the proper filter is selected.

Dick, G.A., "Fabric Filters," Canadian Mining Journal, 91, No. 10, pp 72-80, 1972.

A fabric filter is a device used for freeing process gases and liquids from suspended impurities, and both wet and dry filtration is practiced in the mining industry for particle separation. This paper deals solely with dry filtration and gas cleaning techniques for the recovery of particulate matter to meet air quality control standards. The mining industry has long recognized the need for effective control of airborne contaminants and has used some form of "cloth filter" or "baghouse" for dust control work since the turn of the century. This method of gas cleaning has represented one of the best means of obtaining the highest consistent recovery of gas-borne particulate matter and fabric filters have demonstrated that, when properly operated and maintained, collection efficiencies of airborne particulates can be exceptionally high.

Edmisten, Norman G.; Bunyard, Francis L., "A Systematic Procedure for Determining the Cost of Controlling Particulate Emissions from Industrial Sources," Journal of the Air Pollution Control Association, 20, No. 7, pp 446-452, 1970.

The increasing concern about the air quality of our nation has created a similar concern in the costs associated with reducing emissions to desirable levels. The purpose of this paper is to present a methodology for assessing the cost of controlling particulate emissions from industrial sources. Basic equipment costs were collected and evaluated for dry centrifugal and wet collectors, fabric filters, electrostatic precipitators, and afterburners. Manufacturers, installers, users, and operators of air pollution control equipment were contacted to obtain the necessary cost data for the year 1968. A basic premise of the procedure developed is that the most meaningful approach to the evaluation and comparison of air pollution control costs is based on the total cost of control annualized over the expected economic life of the equipment. Items such as capital charges and expenditures for operation, maintenance, and collected waste disposal are generally more significant in cost accounting than the depreciated value of the initial investment. By defining the size and efficiency of collection required; the degree of difficulty in installing the equipment; and knowledge of some of the characteristics of the involved process, gas stream, and pollutant characteristics, the cost of control can be estimated with the assistance of cost factors and guidelines presented.

Gifford, Franklin A., Jr., "Atmospheric Dispersion," Nuclear Safety, 1, No. 3, pp 56-68, 1960.

One of the chief sources of uncertainty in estimating the hazard associated with accidental or planned release to the atmosphere of fission-product activity has been the lack of reliable measured values of atmospheric dispersion coefficients. In the absence of any obvious alternative, Sutton's well-known mathematical dispersion model has been used in many reactor hazards analyses for evaluating effects far beyond the limits for which the model can confidently be expected to be reliable, e.g., distances of the order of 1 km and near adiabatic (neutral) conditions of atmospheric stability. Consequently, the appearance, in several recent papers, of a sizable quantity of new atmospheric dispersion observations is of considerable interest in connection with the meteorology of nuclear safety problems. Furthermore, the calculation of atmospheric dispersion by the method of moving averages, as has been proposed recently, seems to provide an improved means of calculating dispersion, not only because the technique has less restrictive boundary conditions but also because it is well adapted to the interpretation of continuously monitored atmospheric data.

Gifford, Franklin A., Jr., "Atmospheric Dispersion Calculations Using the Generalized Gaussian Plume Model," Nuclear Safety, 2, No. 2, pp 56-59, 67-68, 1960.

A number of formulas for dealing with various practical dispersion problems that arise in reactor hazard analyses are based on the widely used dispersion model formulated by Sutton. However, results of recent dispersion experiments have more and more often been presented in terms of the simple Gaussian interpolation formula.

Gifford, Franklin A., Jr., "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," Nuclear Safety, 2, No. 4, pp 47-51, 1961.

Estimates of atmospheric dispersion are essential information in the selection of a reactor site and in the evaluation of the hazards of reactor operation. In selecting a site, the dispersion characteristics of the atmosphere at the various sites under consideration are important because most reactors, if not all, generate or induce some atmospheric radioactivity during routine operation and because there is the possibility of accidental release of radioactivity to the atmosphere. Only a few forecasters are familiar with low-level dispersion problems, and consequently it is desirable that simple, easily applied methods of estimating atmospheric dispersion, preferably those employing routine meteorological observations, be discussed.

Gifford, Franklin A., Jr., "The Area Within Ground-Level Dosage Isopleths," Nuclear Safety, 4, No.2, pp 91-92, 97, 1962.

The total radioactive dosage to a population has frequently been identified as an important aspect of the potential hazard associated with reactor accidents.

The total population dosage is equal to the product of people times radioactive dosage, summed over the population, with appropriate high- and low-dosage cutoffs taken into account. To expedite computation of this quantity, it is evidently necessary to be able to calculate the area inside ground-level isodose contours, i.e., the intersection between the surface formed by a given air concentration or dosage value and the ground.

Based on ground-level air-concentration isopleths computed by means of the generalized Gaussian dispersion model is described.

Goldfield, Joseph, "Fabric Filters in Asbestos Mining and Asbestos Manufacturing," APCO Fabric Filter Symposium, Charleston, Virginia, 1971.

Johns-Manville Corporation has hundreds of fabric filters in use in its plants. The advantages of baghouses are their high efficiency and reliability. The largest single baghouse is that installed at the Jeffrey Mill No. 5 in Asbestos, Quebec, Canada. This installation is described in detail. Its overall mass efficiency is 99.992%.

Hailstone, R.E., "Air Pollution Control in the Cement Industry," Minerals Processing, 10, No. 5, pp 11-15, 1969.

There are many technical difficulties to adapt presently available emission control devices to this complex manufacturing process of cement making. Controlling emissions within the limits of recently enacted or pending air pollution control regulations are great in magnitude and cost. Neglect of any one of a multitude of design parameters, or inadequate, improper design of control devices can make a continuous high level operating efficiency essentially impossible to attain.

Increased technology may permit further emission control improvements but at high cost. Proper emphasis should now be placed on the "technically feasible, economically reasonable, practically enforceable" air pollution control regulation, and logical priorities. The portland cement industry recognizes that only through the cooperative efforts of the control agency, the public and industry will it be able to achieve the goals of desirable air quality levels.

Hills, D.W., "Economics of Dust Control," Annals of the New York Academy of Science, 132, pp 322-334, 1964.

A brief historical introduction is given about conditions in the U.K. asbestos textile industry in the late 1920's and early 1930's; reference is made to the 1931 conference between employers and the Home Office that resulted in a code of practice being established for dust suppression in asbestos textile factories. Details are given of the various methods used for dust control in the Company's factories together with the cost of these measures. Some figures are also given for the cost of dust control at the Cape Asbestos Company, Ltd.'s new amosite mill at Penge. Current work on improving dust control is discussed together with the part now played in this by the Asbestosis Research Council.

Although asbestos textiles form only a part of the asbestos industry, their particular significance for this monograph is that, at least in the United Kingdom, the hazards associated with the processing of asbestos were recognized sooner on the textile side than almost anywhere else. This was because most of the processes were dry, and hence dust was readily formed, and also because the workers in some of the largest factories formed a close-knit population whose employment records went back for many years. Thus, when the hazard was first investigated, an excellent sample of people with varying periods of exposure to dust was available.

Hussey, A.M.W., "Dust Collection in Industry," Filtration and Separation, 10, No. 2, pp 181-188, 1973.

The author describes the four basic types of dust collection equipment: cyclone collectors, wet scrubbers, bag filters, and electrical precipitators, and discusses some of their major applications. He emphasizes that a successful installation requires complete understanding between supplier and user and to assist towards this he summarizes equipment selection data which should be considered when installations are being planned.

Jensen, Kenneth, E., "Concepts of Fabric Filtration for Air Pollution Control," Filtration and Separation, 6, No. 3, pp 254,257, 1969.

A brief review of other accepted methods of air and gas cleaning equipment would be in order to relate them to cloth filtration.

Where conditions permit, the filtration of gases through a fabric media offers a number of advantages: efficiencies down to the sub-micron range is inherent; there is a positive barrier in place that does not depend on supplementary devices or materials such as water, changes in direction, or electrical charges; and there is no secondary pollution problem. The material collected in a dry state is re-usable if this is desired and in some cases can be sold to help offset collection costs.

The application of a fabric collector to a dust collection problem is not, however, completely dependent upon economic and efficiency factors. The physical conditions that prevail have a great bearing on whether or not cloth collection is the proper answer.

Jones, Allen H., "How to Improve Maintenance of Fabric Dust Collectors," Minerals Processing, 10, No. 5, pp 254,257, 1969.

The key to low maintenance of a cloth dust collection system is early detection of problems. Dust collection systems are self destructive once they begin to malfunction and small problems becomes disasters very rapidly. Trouble in one part of a system can affect another in a short period of time.

Weekly visual inspection of a collection system combined with proper measurements is mandatory to maintain low cost maintenance, free from shut-downs and crises.

The only way to accurately evaluate dust filter performance and to anticipate maintenance trouble is to take manometer, pilot tube, ammeter, and tachometer readings. If these readings are taken on a regular basis and compared with former readings it will not be necessary to wait for disaster to hit.

Lundgren, D.A.; Greene, V.W., "Filtration and Dust Control Equipment in the Production of Controlled Air Environments," Filtration and Separation, 5, No. 5, pp 405-412, 1968.

After summarizing information which is basic to the design and operational problems of controlling the contamination level of air within an enclosure, the authors discuss performance and cost criteria for selecting air cleaning devices. They deal in turn with the characteristics of seven types of air filters and other dust control devices and conclude by considering the problems of controlling microbes in air.

Minifie, F.G.; Moyes, A.J., "Low Cost Electrostatic Precipitation," Filtration and Separation, 9, No. 1, pp 52-59, 1972.

Three well-known types of dust collector are compared and contrasted. The phenomena occurring in an electrostatic precipitator are described to show why the various components are needed. The factors which lead to heavy costs in electrostatic precipitator construction are described. Means of reducing these costs, using unit precipitators of pre-established design, are indicated. Costs of installing three types of dust collector on two different duties are compared, and the fallacy that electrostatic precipitators are expensive is dispelled.

Minnick, L. John, "Control of Particulate Emissions from Lime Plants - A Survey," Journal of the Air Pollution Control Association, 21, No. 4, pp 195-200, 1971.

This paper describes the achievements of the lime industry in developing methods of handling and controlling the various finely divided products which they produce. An extensive survey provides useful data on the availability and performance of many of the control devices that are currently in use, and an analysis is made of the operating efficiencies and costs of this equipment. The environmental control programs which are currently underway in this industry are described, and an evaluation is made of these programs. The ultimate goals that are believed to be attainable are presented from the standpoint of emission control from individual processes as well as from operating plant complexes. While the paper deals primarily with practical operating and engineering aspects of the subject, some information is also included on methods of tests and the monitoring systems that are in use.

Morrison, Joseph N., Jr., "Controlling Dust Emissions at Belt Conveyor Transfer Points," *Transactions of the Society of Mining Engineers*, 250, No. 1, pp 47-53, 1971.

A comprehensive solution is offered to the problem of dust emissions at belt conveyor transfer points. Details of enclosure design are discussed and a straightforward procedure for calculating required dust control exhaust volume is presented. Many design variables are taken into account which heretofore have been commonly ignored or inadequately considered. These include belt widths, belt speeds, enclosure openings, material flow rate, material bulk densities, material lump sizes, height of material fall, material temperature, and ambient air temperature. All of these questions are handled by means of a "fill-in-the-blanks" type of calculation form, permitting quick, reliable solutions by relative "non-experts."

Pasquill, F., "The Estimation of the Dispersion of Windborne Material," *The Meteorological Magazine*, 90, No. 1063, pp 33-49, 1961.

The theoretical estimation of the concentrations arising from sources of gaseous or finely divided particulate material has for long been based on treatments of atmospheric diffusion developed by Sir Graham Sutton. These formulae are reliable for specifying the average distribution, over a few hundred meters downwind of a source operating for a few minutes on level unobstructed terrain, with a steady wind direction and neutral conditions of atmospheric stability. Extension to other circumstances has depended on empirical and often speculative adjustments of the diffusion parameters.

During the last few years, investigations have shown that a fairly rational allowance can now be made for the effects of much of the wide variation in atmospheric turbulence which occurs in reality. This progress includes some extension to longer distances of travel.

The purpose of this article is to review the recent background of theoretical and experimental results, and to give details of the proposed system of calculating the distribution of concentration downwind of a source. These details are set out in two appendices, the first giving complete instructions for carrying out the calculations, the second presenting an example.

Popa, Bazil; Jancau, Vasile, "The Probability of Certain Concentrations in the Dispersion of Solid Dust Particles in Industrial Regions," Staub-Reinhaltung der Luft, 33, No. 1, pp 20-24, 1973.

The measurement of particulate components in the air is necessary to the health of a community. The prediction of concentrations of particulates is necessary for the planning of controls on present sources and the introduction of new industry, i.e., new sources in the region.

The influence of the wind is of prime importance; not only its speed, but its direction, is discussed. Wind is a random variable and mathematical presentation using statistics are given. Various distribution curves (exponential, logistic, Fisher-Tippett type II (Frechent) and type I (Gumbel), Cauchy, normal Laplace-Gauss) are compared. The town of Chy, Romania is used as an example.

Pring, R.T., "Reducing Baghouse Maintenance by Design," Minerals Processing, 11, No. 5, pp 8-13, 1970.

Structural baghouses comprise one branch of the fabric collector family and are characterized by:

1. Large volume capacity
2. Normally high-temperature service
3. Custom design to fill specific needs
4. Use of large diameter filter bags

5. Absence of internal moving parts
6. Suitability for continuous heavy duty service

Because of design flexibility, baghouses can be furnished in almost infinite configurations and, within reason, at almost any price the purchaser is willing to pay - ranging from the "Model T" to the "Cadillac". Further, the choice of accessories can affect cost materially.

Because the very substantial investment in air pollution control equipment returns no profit, the industry-wide tendency is, understandably, to keep capital costs to an absolute minimum. It is suggested that familiarity with the many available options in design and accessories and how they affect maintenance and operation will help prevent problems after startup.

Rajhans, Gyan S., "Fibrous Dust - Its Measurement and Control," The Canadian Mining and Metallurgical Bulletin, 63, No. 8, pp 900-910, 1970.

The strategy of fibrous dust sampling is discussed, various sampling methods are critically reviewed and their application to coal dust is demonstrated. Fiber counting is described in detail. An attempt is made to explain the basis of determining the threshold limit value of asbestos and other dusts.

The paper also discusses such dust control methods as enclosure of the process, effective local exhaust ventilation, segregation, substitution, wet processing, and continuous monitoring of the return air for recirculation.

Reigel, S.A.; Bundy, R.P.; Doyle, C.D., "Baghouses - What to Know Before You Buy," Pollution Engineering, 5, No. 5, pp 32-34, 1973.

With the advent of stricter emission standards designed to produce the national quality standard of 75 $\mu g/m^3$ of particulate, only the most efficient removal devices will be suitable. The baghouse traditionally yields high removal efficiencies (99.9+ %).

Reitze, William B.; Haladay, D.A.; Romer, Harold; Fenner, E.M., "Control of Asbestos Fiber Emissions from Industrial and Commercial Sources," Proceedings of the Second International Clean Air Congress, pp 100-103, 1970.

There are five major sources from which asbestos fiber enters the air: (1) mining; (2) milling; (3) manufacturing; (4) certain segments of the construction industry; and (5) naturally occurring sources. The first four are created by modern man's technology and the last by normally occurring changes in our environment.

The operations of each source with controls that are now in use are listed.

Roper, G.W., "Asbestos Mill Filters," IIT Research Institute Seminar on Asbestos, 1972.

The asbestos milling industry is the largest user of cloth filters of all industries, since the separation of the fibers from the ore is done pneumatically. Dust collection systems installed by the Wheelabrator Corporation at various asbestos mills are described.

Rozovsky, H., "Air in Asbestos Milling," Canadian Mining Journal, 78, pp 95-103, 1957.

The production of asbestos fiber in modern times depends almost completely on air movement. Almost every part of the operation employs air. Whether it is for ventilation and dust control or for drying, separation or conveying, air is required.

Nearly 400 tons of air per minute are employed in all phases of this industry in Canada. It is readily apparent that to move this 10,000,000 cfm a considerable amount of power and equipment is required. Nearly 90% of this air is used directly in drying and milling processes.

The purpose of this paper is to discuss the importance of air and its use in asbestos milling plants.

Rushton, A.; Griffiths, P.V.R., "Role of Cloth in Filtration," Filtration and Separation, 9, No. 1, pp 81-89, 106, 1972.

The influence of cloth weave patterns on the permeability of clean monofilament and multifilament cloths is presented and a successful correlation of pressure drop-flow data is reported for several cloth types. The effect of cloth pore structure on the mechanisms of cake deposition and the conditions required for bridging the pore is discussed.

Schoek, V.E., "In Mechanical Dust Collectors, It's the Fabric that Really Counts," Engineering and Mining Journal, 173, No. 1, pp 98-99, 1972.

Baghouse filters for reducing particulate emissions and recovering metal values are becoming more efficient, thanks to better filter fabrics. Here are some tips on fabric selection and installation.

Selikoff, I.J.; Hammond, E.C.; Heimann, E., "Critical Evaluation of Disease Hazards Associated with Community Asbestos Air Pollution," Proceedings of the Second International Clean Air Congress, pp 165-171, 1970.

The results of 3,000 consecutive autopsies in New York City is correlated with asbestos bodies. The results of sampling the ambient air of New York City show an asbestos air level of 11-60 x 10^{-9} g/m^3. Types of exposure as well as sources and control methods are discussed.

Sullivan, Ralph J.; Athanassiadis, Yanis C., Air Pollution Aspects of Asbestos, National Air Pollution Control Administration, No. PH-22-68-25, Washington, D.C., 1969.

Inhalation of asbestos may cause asbestosis, pleural or peritoneal mesothelioma, or lung cancer. Mesothelioma is a rare form of cancer which occurs frequently in asbestos workers. All three of these diseases are fatal once they become established. The dose necessary to produce asbestosis has been estimated to be 50 to 60 million particles per cubic foot-years. No information is available on the dose necessary to induce cancer. Random autopsies of lungs have shown "asbestos bodies" in the lungs of one-fourth to one-half fo samples from urban populations. Thus, the apparent air pollution by asbestos reaches a large number of people.

Animals have been shown to develop asbestosis and cancer after exposure to asbestos.

No information has been found on the effects of asbestos air pollution on plants or materials.

The likely sources of asbestos air pollution are uses of the asbestos products in the consturction industry and asbestos mines and factories. Observations in Finland and Russia indicate that asbestos does pollute air near mines and factories. However, no measurements were reported of the concentration of asbestos near likely sources in the United States. A concentration in urban air of 600 to 6,000 particles per cubic meter has been estimated.

Bag filters have been used in factories to control asbestos emissions; the cost of this type of control in a British factory was approximately 27.5 percent of the total capital cost and about 7 percent of the operating cost. No information has been found on the costs of damage resulting from asbestos air pollution.

No satisfactory analytical method is available to determine asbestos in the atmosphere.

Turner, D.Bruce, Workbook of Atmospheric Dispersion Estimates, National Air Pollution Control Administration, Cincinnati, 1970.

This workbook presents methods of practical application of the binormal continuous plume dispersion model to estimate concentrations of air pollutants. Estimates of dispersion are those of Pasquill as restated by Gifford. Emphasis is on the estimation of concentrations from continuous sources for sampling times up to 1 hour. Some of the topics discussed are determination of effective height of emission, extension of concentration estimates to longer sampling intervals, inversion break-up fumigation concentrations, and concentrations from area, line, and multiple sources. Twenty-six example problems and their solutions are given. Some graphical aids to computation are included.

Werle, Donald K., "Fabric Filters in Pollution Control," IIT Research Institute internal report No. IITRI-C8196-T4, 1972.

Fibrous filters are commonly used in the cleaning of air for ventilation purposes and for industrial gas cleaning. The latter application, of primary interest in this report, can involve the cleaning of gases with very high dust loadings, and many filter fabrics are available for use where corrosive gases or moderate temperatures are involved. The intent of the report is to cover the operating principles, design methodology, economics, and application of fabric filters in air pollution control.

Wieschhaus, L.J., "Recovering Asbestos Floats with Dust Collectors," Rock Products, 50, No. 8, pp 104-105, 1947.

Dust clouds created in the milling of asbestos have long defied efficient and economical collection and it is only recently that this problem has been successfully solved. Because of the vast quantities of asbestos lost in the form of dust and because of the high market value of these "floats" at the present time, it may be well to consider some of the factors involved in the collection of asbestos.

Appendix B

BINORMAL CONTINUOUS PLUME DISPERSION MODEL RESULTS

SYMBOLS USED IN THE FOLLOWING TABLES

x = distance from source downwind in the direction of the mean wind (kilometers)

σ_y = the standard deviation in the crosswind direction of the plume concentration distribution (meters)

σ_z = the standard deviation in the vertical of the plume concentration distribution (meters)

X = fiber concentration (fibers per cubic meter)

OM = number of fibers observed by optical microscope

EM = number of fibers observed by electron microscope

Calculation of Concentrations for Various Distances

JOHNS-MANVILLE CORPORATION ASBESTOS PRODUCTS PLANT
WAUKEGAN, ILLINOIS

Mean Wind Speed: 4.47 m/sec

Source Term -- Based on Optical Microscopy: 1.20×10^5 fibers/sec
Based on Electron Microscope: 2.03×10^8 fibers/sec

Source Height: 10 m

Daytime Mixing Height: 800 m

Nighttime Mixing Height: 150 m

Stability Class B: DAYTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3)	
			OM	EM
0.1	19.0	11.0	2.71×10^{1}	4.58×10^{4}
0.3	52.0	31.0	5.03	8.51×10^{3}
0.5	83.0	51.0	1.98	3.35×10^{3}
0.8	130	85.0	7.68×10^{-1}	1.30×10^{3}
1.0	158	109	4.94×10^{-1}	8.36×10^{2}
2.0	290	233	1.26×10^{-1}	2.13×10^{2}
3.0	420	360	5.65×10^{-2}	9.56×10^{1}
3.1	440	370	5.25×10^{-2}	8.88×10^{1}
6.2	800	800	2.37×10^{-2}	4.01×10^{1}
7.0	880	800	2.15×10^{-2}	3.64×10^{1}
10.0	1,200	800	1.58×10^{-2}	2.67×10^{1}
15.0	1,700	800	1.11×10^{-2}	1.88×10^{1}
20.0	2,150	800	8.81×10^{-3}	1.49×10^{1}
30.0	3,050	800	6.21×10^{-3}	1.05×10^{1}

Stability Class C: DAYTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3)	
			OM	EM
0.1	12.5	7.5	3.76×10^{1}	6.36×10^{4}
0.3	34.0	20.5	1.09×10^{1}	1.84×10^{4}
0.5	55.0	30.2	4.87	8.24×10^{3}
0.8	86.0	49.0	1.99	3.37×10^{3}
1.0	105	61.0	1.32	2.23×10^{3}
2.0	200	115	2.70×10^{-1}	6.26×10^{2}
3.0	285	170	1.76×10^{-1}	2.98×10^{2}
5.0	450	265	7.16×10^{-2}	1.21×10^{2}
6.5	570	340	4.41×10^{-2}	7.46×10^{1}
7.3	630	380	3.57×10^{-2}	6.04×10^{1}
14.6	1,150	800	1.65×10^{-2}	2.79×10^{1}
17.0	1,330	800	1.42×10^{-2}	2.40×10^{1}
20.0	1,520	800	1.25×10^{-2}	2.11×10^{1}
25.0	1,850	800	1.02×10^{-2}	1.73×10^{1}
30.0	2,170	800	8.72×10^{-3}	1.48×10^{1}

Stability Class D: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3)	
			OM	EM
0.1	8.1	4.6	2.18×10^{1}	3.69×10^{4}
0.3	22.0	12.0	2.29×10^{1}	3.87×10^{4}
0.5	36.0	17.5	1.15×10^{1}	1.95×10^{4}
0.8	55.0	26.5	5.46	9.24×10^{3}
1.0	67.0	31.5	2.85	6.51×10^{3}
2.0	130	49.0	1.31	2.22×10^{3}
3.0	188	64.0	7.02×10^{-1}	1.19×10^{3}
3.5	215	71.0	5.54×10^{-1}	9.37×10^{2}
7.0	400	150	2.52×10^{-1}	4.26×10^{2}
10.0	550	150	1.84×10^{-1}	3.11×10^{2}
15.0	790	150	1.28×10^{-1}	2.17×10^{2}
20.0	990	150	1.02×10^{-1}	1.73×10^{2}
30.0	1,430	150	7.06×10^{-2}	1.19×10^{2}

Stability Class E: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3)	
			OM	EM
0.1	6.0	3.5	6.80	1.15×10^4
0.3	16.5	8.8	3.07×10^1	5.19×10^4
0.5	26.5	13.0	1.85×10^1	3.13×10^4
0.8	40.0	18.0	1.02×10^1	1.73×10^4
1.0	50.0	21.3	6.97	1.18×10^4
2.0	95.0	33.5	2.57	4.35×10^3
3.0	140	43.0	1.38	2.33×10^3
5.0	220	55.0	6.95×10^{-1}	1.18×10^3
8.0	335	71.0	3.56×10^{-1}	6.02×10^2
16.0	620	150	1.63×10^{-1}	2.76×10^2
20.0	750	150	1.35×10^{-1}	2.28×10^2
25.0	920	150	1.10×10^{-1}	1.86×10^2
30.0	1,070	150	9.44×10^{-2}	1.60×10^2

Calculation of Concentrations for Various Distances

JOHNS-MANVILLE CORPORATION ASBESTOS CEMENT PIPE PLANT
DENISON, TEXAS

Mean Wind Speed: 4.07 m/sec

Source Term -- Based on Optical Microscopy: 3.53×10^5 fibers/sec
Based on Electron Microscopy: 1.69×10^8 fibers/sec

Source Height: 10 m

Daytime Mixing Height: 800 m

Nighttime Mixing Height: 150 m

Stability Class B: DAYTIME

x (km)	σ_y (m)	σ_z (m)	χ (fibers/m^3)	
			OM	EM
0.1	19.0	11.0	8.74×10^1	4.18×10^4
0.3	52.0	31.0	1.70×10^1	8.14×10^3
0.5	83.0	51.0	6.40	3.06×10^3
0.8	130	85.0	2.48	1.19×10^3
1.0	158	109	1.60	7.66×10^2
2.0	290	233	4.08×10^{-1}	1.95×10^2
3.0	420	360	1.83×10^{-1}	8.76×10^1
3.1	440	370	1.70×10^{-1}	8.14×10^1
6.2	800	800	7.65×10^{-2}	3.66×10^1
7.0	880	800	6.95×10^{-2}	3.33×10^1
10.0	1,200	800	5.10×10^{-2}	2.44×10^1
15.0	1,700	800	3.60×10^{-2}	1.72×10^1
20.0	2,150	800	2.84×10^{-2}	1.36×10^1
30.0	3,050	800	2.01×10^{-2}	9.62

Stability Class C: DAYTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	X (fibers/m^3) EM
0.1	12.5	7.5	1.22×10^{2}	5.84×10^{4}
0.3	34.0	20.5	3.52×10^{1}	1.69×10^{4}
0.5	55.0	30.2	1.57×10^{1}	7.52×10^{3}
0.8	86.0	49.0	6.41	3.07×10^{3}
1.0	105	61.0	4.25	2.03×10^{3}
2.0	200	115	1.20	5.75×10^{2}
3.0	285	170	5.69×10^{-1}	2.72×10^{2}
5.0	450	265	2.31×10^{-1}	1.11×10^{2}
6.5	570	340	1.42×10^{-1}	6.80×10^{1}
7.3	630	380	1.15×10^{-1}	5.51×10^{1}
14.6	1,150	800	5.32×10^{-2}	2.55×10^{1}
17.0	1,330	800	4.60×10^{-2}	2.20×10^{1}
20.0	1,520	800	4.02×10^{-2}	1.92×10^{1}
25.0	1,850	800	3.31×10^{-2}	1.58×10^{1}
30.0	2,170	800	2.82×10^{-2}	1.35×10^{1}

Stability Class D: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	X (fibers/m^3) EM
0.1	8.1	4.6	6.96×10^{1}	3.33×10^{4}
0.3	22.0	12.0	7.39×10^{1}	3.54×10^{4}
0.5	36.0	17.5	3.72×10^{1}	1.78×10^{4}
0.8	55.0	26.5	1.76×10^{1}	8.43×10^{3}
1.0	67.0	31.5	1.24×10^{1}	5.94×10^{3}
2.0	130	49.0	4.24	2.03×10^{3}
3.0	188	64.0	2.27	1.09×10^{3}
3.5	215	71.0	1.79	8.57×10^{2}
7.0	400	150	8.16×10^{-1}	3.91×10^{2}
10.0	550	150	5.93×10^{-1}	2.84×10^{2}
15.0	790	150	4.13×10^{-1}	1.98×10^{2}
20.0	990	150	3.30×10^{-1}	1.58×10^{2}
30.0	1,430	150	2.28×10^{-1}	1.09×10^{2}

Stability Class E: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	X (fibers/m^3) EM
0.1	6.0	3.5	2.20×10^1	1.05×10^4
0.3	16.5	8.8	9.93×10^1	4.75×10^4
0.5	26.5	13.0	5.96×10^1	2.85×10^4
0.8	40.0	18.0	3.29×10^1	1.58×10^4
1.0	50.0	21.3	2.25×10^1	1.08×10^4
2.0	95.0	33.5	8.29	3.97×10^3
3.0	140	43.0	4.46	2.14×10^3
5.0	220	55.0	2.25	1.08×10^3
8.0	335	71.0	1.15	5.51×10^2
16.0	620	150	5.26×10^{-1}	2.52×10^2
20.0	750	150	4.35×10^{-1}	2.08×10^2
25.0	920	150	3.55×10^{-1}	1.70×10^2
30.0	1,070	150	3.05×10^{-1}	1.46×10^2

Calculation of Concentrations for Various Distances

RAYBESTOS - MANHATTAN ASBESTOS TEXTILE MANUFACTURING PLANT
MARSHVILLE, NORTH CAROLINA

Mean Wind Speed: 3.35 m/sec

Source Term -- Based on Optical Microscopy: 1.12×10^5 fibers/sec
Based on Electron Microscopy: 3.97×10^{10} fibers/sec

Source Height: 10 m

Daytime Mixing Height: 800 m

Nighttime Mixing Height: 150 m

Stability Class B: DAYTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	X (fibers/m^3) EM
0.1	19.0	11.0	3.37×10^1	1.19×10^7
0.3	52.0	31.0	6.27	2.22×10^6
0.5	83.0	51.0	2.47	8.76×10^5
0.8	130	85.0	9.56×10^{-1}	3.39×10^5
1.0	158	109	6.15×10^{-1}	2.28×10^5
2.0	290	233	1.57×10^{-1}	5.57×10^5
3.0	420	360	7.04×10^{-2}	2.50×10^4
3.1	440	370	6.54×10^{-2}	2.32×10^4
6.2	800	800	2.95×10^{-2}	1.05×10^4
7.0	880	800	2.68×10^{-2}	9.50×10^3
10.0	1,200	800	1.96×10^{-2}	6.95×10^3
15.0	1,700	800	1.39×10^{-2}	4.92×10^3
20.0	2,150	800	1.10×10^{-2}	3.90×10^3
30.0	3,050	800	7.73×10^{-3}	2.74×10^3

Stability Class C: DAYTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	X (fibers/m^3) EM
0.1	12.5	7.5	4.69×10^{1}	1.66×10^{7}
0.3	34.0	20.5	1.36×10^{1}	4.82×10^{6}
0.5	55.0	30.2	6.07	2.15×10^{6}
0.8	86.0	49.0	2.47	8.76×10^{5}
1.0	105	61.0	1.64	5.81×10^{5}
2.0	200	115	4.61×10^{-1}	1.63×10^{5}
3.0	285	170	2.19×10^{-1}	7.76×10^{4}
5.0	450	265	8.92×10^{-2}	3.16×10^{4}
6.5	570	340	5.49×10^{-2}	1.95×10^{4}
7.3	630	380	4.45×10^{-2}	1.58×10^{4}
14.6	1,150	800	2.05×10^{-2}	7.27×10^{3}
17.0	1,330	800	1.77×10^{-2}	6.27×10^{3}
20.0	1,520	800	1.55×10^{-2}	5.49×10^{3}
25.0	1,850	800	1.27×10^{-2}	4.50×10^{3}
30.0	2,170	800	1.09×10^{-2}	8.86×10^{3}

Stability Class D: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	X (fibers/m^3) EM
0.1	8.1	4.6	2.71×10^{1}	9.61×10^{6}
0.3	22.0	12.0	2.85×10^{1}	1.01×10^{7}
0.5	36.0	17.5	1.44×10^{1}	5.10×10^{6}
0.8	55.0	26.5	6.80	2.41×10^{6}
1.0	67.0	31.5	4.80	1.70×10^{6}
2.0	130	49.0	1.64	5.81×10^{5}
3.0	188	64.0	8.74×10^{-1}	3.10×10^{5}
3.5	215	71.0	6.90×10^{-1}	2.45×10^{5}
7.0	400	150	3.14×10^{-1}	1.11×10^{5}
10.0	550	150	2.29×10^{-1}	8.12×10^{4}
15.0	790	150	1.59×10^{-1}	5.64×10^{4}
20.0	990	150	1.27×10^{-1}	4.50×10^{4}
30.0	1,430	150	8.79×10^{-2}	3.12×10^{4}

Stability Class E: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	X (fibers/m^3) EM
0.1	6.0	3.5	8.46	3.00×10^6
0.3	16.5	8.8	3.83×10^1	1.36×10^7
0.5	26.5	13.0	2.30×10^1	8.15×10^6
0.8	40.0	18.0	1.27×10^1	4.50×10^6
1.0	50.0	21.3	8.68	3.08×10^6
2.0	95.0	33.5	3.20	1.13×10^6
3.0	140	43.0	1.72	6.10×10^5
5.0	220	55.0	8.65×10^{-1}	3.07×10^5
8.0	335	71.0	4.43×10^{-1}	1.57×10^5
16.0	620	150	2.03×10^{-1}	7.20×10^4
20.0	750	150	1.68×10^{-1}	5.95×10^4
25.0	920	150	1.37×10^{-1}	4.86×10^4
30.0	1,070	150	1.18×10^{-1}	4.18×10^4

Calculation of Concentrations for Various Distances

JOHNS-MANVILLE CORPORATION MILL NO. 5
ASBESTOS, QUEBEC, CANADA

Mean Wind Speed: 3.89 m/sec

Source Term -- Based on Optical Microscopy: 7.63×10^8 fibers/sec
Based on Electron Microscopy: 3.05×10^{12} fibers/sec

Source Height: 40 m

Daytime Mixing Height: 800 m

Nighttime Mixing Height: 150 m

Stability Class B: DAYTIME

x (km)	σ_y (m)	σ_z (m)	χ (fibers/m^3) OM	χ (fibers/m^3) EM
0.1	19.0	11.0	3.97×10^2	1.58×10^6
0.3	52.0	31.0	1.68×10^4	6.72×10^7
0.5	83.0	51.0	1.08×10^4	4.32×10^7
0.8	130	85.0	5.05×10^3	2.02×10^7
1.0	158	109	3.39×10^3	1.36×10^7
2.0	290	233	9.10×10^2	3.64×10^6
3.0	420	360	4.10×10^2	1.64×10^6
3.1	440	370	3.82×10^2	1.53×10^6
6.2	800	800	1.73×10^2	6.92×10^5
7.0	880	800	1.57×10^2	6.28×10^5
10.0	1,200	800	1.15×10^2	4.60×10^5
15.0	1,700	800	8.14×10^1	3.25×10^5
20.0	2,150	800	6.44×10^1	2.57×10^5
30.0	3,050	800	4.53×10^1	1.81×10^5

Stability Class C: DAYTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3)	
			OM	EM
0.1	12.5	7.5	4.52×10^{-1}	1.81×10^{3}
0.3	34.0	20.5	1.33×10^{4}	5.31×10^{7}
0.5	55.0	30.2	1.57×10^{4}	6.28×10^{7}
0.8	86.0	49.0	1.06×10^{4}	4.24×10^{7}
1.0	105	61.0	7.86×10^{3}	3.14×10^{7}
2.0	200	115	2.55×10^{3}	1.02×10^{7}
3.0	285	170	1.25×10^{3}	5.00×10^{6}
5.0	450	265	5.18×10^{2}	2.07×10^{6}
6.5	570	340	3.20×10^{2}	1.28×10^{6}
7.3	630	380	2.59×10^{2}	1.04×10^{6}
14.6	1,150	800	1.20×10^{2}	4.80×10^{5}
17.0	1,330	800	1.04×10^{2}	4.16×10^{5}
20.0	1,520	800	9.10×10^{1}	3.64×10^{5}
25.0	1,850	800	7.48×10^{1}	2.99×10^{5}
30.0	2,170	800	6.37×10^{1}	2.55×10^{5}

Stability Class D: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3)	
			OM	EM
0.1	8.1	4.6	6.15×10^{-11}	2.46×10^{-7}
0.3	22.0	12.0	9.25×10^{2}	3.70×10^{6}
0.5	36.0	17.5	7.20×10^{3}	2.88×10^{7}
0.8	55.0	26.5	1.37×10^{4}	5.48×10^{7}
1.0	67.0	31.5	1.32×10^{4}	5.28×10^{7}
2.0	130	49.0	7.03×10^{3}	2.81×10^{7}
3.0	188	64.0	4.27×10^{3}	1.71×10^{7}
3.5	215	71.0	3.49×10^{3}	1.40×10^{7}
7.0	400	150	1.84×10^{3}	7.36×10^{6}
10.0	550	150	1.34×10^{3}	5.36×10^{6}
15.0	790	150	9.34×10^{2}	3.73×10^{6}
20.0	990	150	7.45×10^{2}	2.98×10^{6}
30.0	1,430	150	5.16×10^{2}	2.06×10^{6}

Stability Class E: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	 EM
0.1	6.0	3.5	1.79×10^{-22}	7.16×10^{-19}
0.3	16.5	8.8	1.38×10^{1}	5.52×10^{3}
0.5	26.5	13.0	1.58×10^{3}	6.32×10^{6}
0.8	40.0	18.0	7.38×10^{3}	2.95×10^{7}
1.0	50.0	21.3	1.00×10^{4}	4.00×10^{7}
2.0	95.0	33.5	7.67×10^{3}	3.87×10^{7}
3.0	140	43.0	6.73×10^{3}	2.69×10^{7}
5.0	220	55.0	3.96×10^{3}	1.58×10^{7}
8.0	335	71.0	2.24×10^{3}	8.95×10^{6}
16.0	620	150	1.19×10^{3}	4.76×10^{6}
20.0	750	150	9.8×10^{2}	3.93×10^{6}
25.0	920	150	8.02×10^{2}	3.21×10^{6}
30.0	1,070	150	6.89×10^{2}	2.75×10^{6}

Calculations of Concentrations for Various Distances

GAF, INCORPORATED ASBESTOS MILL
EDEN MILLS, VERMONT

Mean Wind Speed: 3.89 m/sec

Source Term -- Based on Optical Microscopy: 6.40×10^6 fibers/sec
Based on Electron Microscopy: 1.83×10^{10} fibers/sec

Source Height: 20 m

Daytime Mixing Height: 800 m

Nighttime Mixing Height: 150 m

Stability Class B: DAYTIME

x (km)	σ_y (m)	σ_z (m)	χ (fibers/m^3) OM	χ (fibers/m^3) EM
0.1	19.0	11.0	4.79×10^2	1.32×10^6
0.3	52.0	31.0	2.64×10^2	7.55×10^5
0.5	83.0	51.0	1.15×10^2	3.29×10^5
0.8	130	85.0	4.61×10^1	1.32×10^5
1.0	158	109	2.99×10^1	8.55×10^4
2.0	290	233	7.72	2.21×10^4
3.0	420	360	3.46	9.89×10^3
3.1	440	370	3.21	9.18×10^3
6.8	800	800	1.45	4.15×10^3
7.0	880	800	1.32	3.77×10^3
10.0	1,200	800	9.67×10^{-1}	2.77×10^3
15.0	1,700	800	6.83×10^{-1}	1.95×10^3
20.0	2,150	800	5.40×10^{-1}	1.54×10^3
30.0	3,050	800	3.80×10^{-1}	1.09×10^3

Stability Class C: DAYTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3)	
			OM	EM
0.1	12.5	7.5	1.58×10^{2}	4.52×10^{5}
0.3	34.0	20.5	4.67×10^{2}	1.34×10^{6}
0.5	55.0	30.2	2.53×10^{2}	7.23×10^{5}
0.8	86.0	49.0	1.14×10^{2}	3.26×10^{5}
1.0	105	61.0	7.55×10^{1}	2.22×10^{5}
2.0	200	115	2.24×10^{1}	6.40×10^{4}
3.0	285	170	1.07×10^{1}	3.06×10^{4}
5.0	450	265	4.38	1.25×10^{4}
6.5	570	340	2.70	7.72×10^{3}
7.3	630	380	2.19	6.26×10^{3}
14.6	1,150	800	1.01	2.89×10^{3}
17.0	1,330	800	8.72×10^{-1}	2.49×10^{3}
20.0	1,520	800	7.63×10^{-1}	2.18×10^{3}
25.0	1,850	800	6.27×10^{-1}	1.79×10^{3}
30.0	2,170	800	5.35×10^{-1}	1.53×10^{3}

Stability Class D: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3)	
			OM	EM
0.1	8.1	4.6	1.09	3.12×10^{3}
0.3	22.0	12.0	4.92×10^{2}	1.41×10^{6}
0.5	36.0	17.5	4.34×10^{2}	1.26×10^{6}
0.8	55.0	26.5	2.70×10^{2}	7.72×10^{5}
1.0	67.0	31.5	2.03×10^{2}	5.80×10^{5}
2.0	130	49.0	7.56×10^{1}	2.16×10^{5}
3.0	188	64.0	4.14×10^{1}	1.18×10^{5}
3.5	215	71.0	3.30×10^{1}	9.49×10^{4}
7.0	400	150	1.55×10^{1}	4.43×10^{4}
10.0	550	150	1.13×10^{1}	3.23×10^{4}
15.0	790	150	7.83	2.24×10^{4}
20.0	990	150	6.25	1.79×10^{4}
30.0	1,430	150	4.33	1.24×10^{4}

Stability Class E: NIGHTTIME

x (km)	σ_y (m)	σ_z (m)	X (fibers/m^3) OM	 EM
0.1	6.0	3.5	2.07×10^{-3}	5.91
0.3	16.5	8.8	2.74×10^{2}	7.83×10^{5}
0.5	26.5	13.0	4.65×10^{2}	1.33×10^{6}
0.8	40.0	18.0	3.93×10^{2}	1.12×10^{6}
1.0	50.0	21.3	3.16×10^{2}	9.04×10^{5}
2.0	95.0	33.5	1.38×10^{2}	3.95×10^{5}
3.0	140	43.0	7.81×10^{1}	2.23×10^{5}
5.0	220	55.0	4.04×10^{1}	1.16×10^{5}
8.0	335	71.0	2.12×10^{1}	6.06×10^{4}
16.0	620	150	9.98	2.85×10^{4}
20.0	750	150	8.25	2.36×10^{4}
25.0	920	150	6.73	1.92×10^{4}
30.0	1,070	150	5.78	1.65×10^{4}